



**OPTIMIZATION MODEL FOR BASE-LEVEL
DELIVERY ROUTES AND
CREW SCHEDULING**

THESIS

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AFIT/GOR/ENS/05-02

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THESIS

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Abstract

In the US Air Force, a Logistic Readiness Squadron (LRS) provides material management, distribution, and oversight of contingency operations. Dispatchers in the LRS must quickly prepare schedules that meet the needs of their customers while dealing with real-world constraints such as time windows, delivery priorities, and intermittent recurring missions. Currently, LRS vehicle operation elements are faced with a shortage of manpower and lack an efficient scheduling algorithm and tool. The purpose of this research is to enhance the dispatchers' capability to handle flexible situations and produce "good" schedules within current manpower restrictions. In this research, a new scheduling model and algorithm are provided as an approach to crew scheduling for a base-level delivery system with a single depot. A Microsoft Excel[®] application, the Daily Squadron Scheduler (DSS), was built to implement the algorithm. DSS combines generated duties with the concept of a set covering problem. It utilizes a Linear Programming pricing algorithm and Excel Solver as the primary engine to solve the problem. Reduced costs and shadow prices from sub problems are used to generate a set of feasible duties from which an optimal solution to the LP relaxation can be found. From these candidate duties the best IP solution is then found. The culmination of this effort was the development of both a scheduling tool and an analysis tool to guide the LRS dispatcher toward efficient current and future schedules.

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Young-ho Cha

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Chapter 1. Introduction

1.1 Background

The 48th Fighter Wing (FW) Royal Air Force (RAF) Lakenheath, England is England's largest U.S. Air Force-operated fighter base. It is located in the northeastern part of London. The 48th Logistic Readiness Squadron (LRS) is part of the 48th Mission Support Group (MSG), and provides materiel management, distribution, and support for contingency operations of the 48th FW, United States Air Forces in Europe (USAFE), US European Command (USEUCOM), and North Atlantic Treaty Organization (NATO) commitments. It manages and operates a large fleet of vehicles, receives, stores, inspects and delivers supplies; delivers petroleum; and directs the wing's deployment and plans program. Figure 1-1 shows the LRS organizational structure.

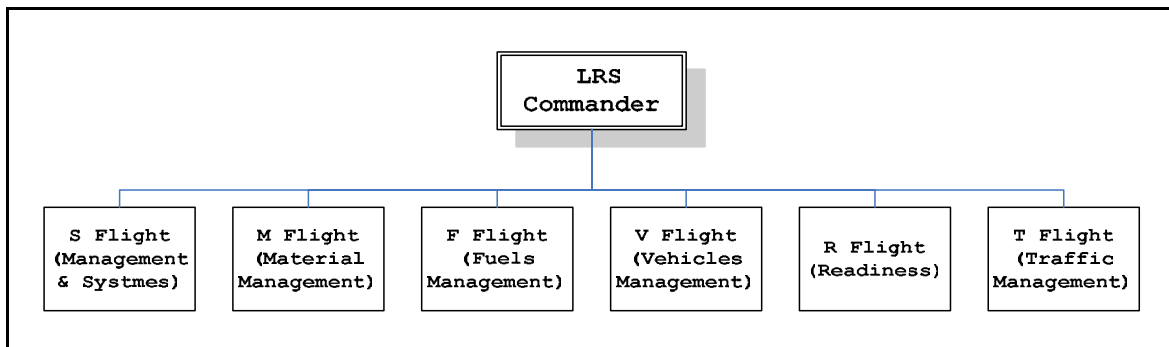


Figure 1-1 LRS Organizational Structure

This thesis is in response to the LRS's request for support. This research focuses on the V Flight. The V Flight is composed of Vehicle Operations and Vehicle Maintenance. Vehicle Operations (VO) include delivery of property to customers across the installation and to possibly geographically separated units using finite resources such as drivers, vehicles, property, and time. The Vehicle Operations Element provides efficient and economical 24-hour-a-day and 7-day-a-week ground traffic support for the wing's peace and wartime rapid deployment mission. This group has five primary responsibilities: (1) pickup and delivery to include Redball deliveries (Redball deliveries are unscheduled and urgent); (2) cargo and passenger movement for all wing deployments; (3) flight line shuttle bus; (4) aircrew shuttle service for all three fighter squadrons (492nd, 493rd, and 494th); (5) Distinguished Visitor(DV) support, taxi and wrecker service. The Vehicle Operations Element's two major priorities are aircrew shuttle and pickup and delivery.

1.2 Problem Statement

The LRS would like to optimize their schedule to support missions, based on their resources. Resources limitations originally determined included number of drivers, customer service time and numbers of vehicles. Fortunately, the LRS now operates a sufficient number of vehicles and, during the course of conducting this research, the vehicle constraints were discarded. The critical resource limitation is crew numbers. The V Flight commander said, "The Pick Up and Delivery workload makes up 42% of the total workload. Our Flight has the right number of personnel just not the right mix of personnel." Table 1-1 explains the current LRS's crew number level and highlights the

shortage of available crew. This is a serious problem for the LRS and is one example of the extremely diverse scheduling challenges faced by LRS schedulers. As well as the shortage of available drivers, the dynamics involved in the many varied and frequently changing requests from various customers (including urgent and important requests) make the scheduling more difficult.

Table 1-1 Personnel Status in LRS

Personnel	Authorized	Assigned	Available
Military(2T1X1)	31	29	16
MoD	21	16	15
DoD	2	2	2

Many locations develop periodic routes for delivery based on the average workday, customer hours, etc. The difficulty in determining the proper mix of resources causes instability in resource availability for other responsible functions as well as delivery. Sometimes overtime is required to support. Scheduled work hours are frequently not sufficient and workers must be paid overtime to accomplish their support tasks.

The chief scheduler in the LRS performs the scheduling processes manually. This decreases the possibility that all customers' requests are covered. Also, the manual scheduling process is vulnerable to daily changes in requirements. Any improvement changing from manual to computerized work in the scheduling process will reduce the possibility of not satisfying some requests. In addition to the benefit to the LRS, better schedules generated more rapidly also allow more time for maintenance to allocate the vehicles for scheduled missions such as periodic inspections, etc. A computerized schedule, therefore, provides the benefit of more efficient resource assignments for both

operators and vehicles. Any tool that can assist scheduling and rescheduling will decrease the amount of time spent on these processes, increase the efficiency of the utilization of resources and also prevent overtasking of individuals.

1.3 Thesis Overview

The scope of this thesis is limited to the planning and generating of a daily operator's schedule, which consists of daily recurring runs and intermittent recurring runs, while maximizing resource usage and maintaining a balanced workload among operators. The model developed in this research also provides a re-scheduling ability to maximize customer satisfaction and maintaining quality of service. This thesis contains four themes. Chapter 2 provides the general information about the scheduling problem and specific information about the scheduling problem at the 48th LRS. Chapter 3 outlines the development of the scheduling model and a heuristic used to solve the scheduling problems of the 48th LRS. In Chapter 4, model results are analyzed. Finally, Chapter 5 gives the summary of the research, contributions and recommendations for future research.

Chapter 2. Literature Review

2.1 Chapter Overview

This chapter covers the concepts of scheduling, the topics related to vehicle routing and crew scheduling theory, and using software-based visual interactive modeling to generate schedules. In addition, the chapter also provides the background of the scheduling environment at the 48th LRS.

2.2 Scheduling Theory

This section introduces concepts from scheduling theory. Scheduling concerns the allocation of limited resources to tasks over time. It is a decision making process that has as a goal the optimization of one or more objectives (Pinedo, 2002:1). Scheduling is a decision-making process that exists in almost all operational environments. A manufacturing facility has to manage the flow of its resources; the arrival of raw material, worker shifts, and the departure of finished products. The scheduling function also faces a variety of different problems in a service organization. One such problem might be dealing with the reservation of resources, e.g., the assignment of aircraft to a future mission even though they are not currently initialized (Pinedo, 2002:6).

The resources and tasks in an organization can take many forms. The resources may be machines in a workshop, runways at an airport, crews at a construction site, a processing unit in a computer environment, and so on. The tasks may be operations in a production process, take offs and landings at an airport, stages in a construction project,

executions of computer programs and so on. The objectives can also take many forms. One objective may be the minimization of the completion time of the last task commonly referred to a ‘makespan’, another may be the minimization of the number of tasks completed after their respective due dates (Pinedo, 2002:1).

2.3 Scheduling Problem

The scheduling problem has attracted much interest from both academia and the operational world (Evren, 1999). Many theoretical research topics are directed towards simple machine scheduling problems. In the operational world, scheduling environments are much more complex and cannot be directly extrapolated to some simple theoretical machine-scheduling model. Pinedo outlines some of the most common problems encountered in scheduling. Empirically, the problems that are relevant to resource scheduling environments are summarized by Pinedo as:

Theoretical models usually assume that there are n jobs to be scheduled and that after scheduling these n jobs, the problem is solved. In reality, new jobs are added or current jobs are re-scheduled continuously. The dynamic nature of resource scheduling in services may require that slack times be built into the schedule in expectation of the unexpected.

Theoretical models usually do not emphasize the *resequencing* problem. In practice, the following problem often occurs: There exists a schedule, which was determined earlier based on certain assumptions, and an (unexpected) random event occurs that requires either major or minor modifications in the existing schedule. The rescheduling process, which is sometimes referred to as *reactive* scheduling, may have to satisfy certain constraints. For example, one may wish to keep the changes in the existing schedule at a minimum even if an optimal schedule cannot be achieved this way. This implies that it is advantageous to construct schedules that are in a sense *robust*. That is, resequencing brings about only minor changes in the schedule. The opposite of robust is often referred to as *brittle*.

Real world scheduling environments are often more complicated than the ones considered in general scheduling theory.

In the mathematical models, the weights (priorities) of the jobs are assumed to be fixed (i.e., they do not change over time). In practice, the weight of a job often fluctuates over time due to changing priorities in the organization or a number of other factors.

Mathematical models often do not take preferences into account. A scheduler may favor some assignment for some reasons that cannot be incorporated into the model.

Most theoretical research has focused on models with a single objective. Most real world problems exhibit multi-criteria and multi-objective characteristics, which sometimes are in conflict with each other (Pinedo, 2002:392).

Pinedo states that scheduling is the decision-making process that exists in most manufacturing and production systems as well as in most information-processing environments (Pinedo, 2002:1). Scheduling in these settings allocates resources to different tasks over a period of time.

2.4 Traveling Salesman and Vehicle Routing Problems

The traveling salesman (agent) problem (TSP) and the vehicle routing problem (VRP) are two classic problems of operations research. The two problems are closely related. In the TSP, a single salesman must visit a set of customers or cities, visiting every customer exactly once, and return home. A cost is associated with travel between two customers. Thus, the objective is to find the lowest cost tour. A tour is an ordered list of customers representing the salesman's cycle through the set of customers. For the single salesman TSP, it is assumed that the salesman has unconstrained ability to pay the cost of the tour. Extensions to this basic problem include the following: multiple

traveling salesmen and time windows for each customer. The literature contains many examples of different varieties of these problems. Lawler et al (1985) discuss the TSP and its variants in depth. The TSP forms the basis for the vehicle routing problem (VRP).

As opposed to the model of a salesman, a vehicle servicing a set of customers is subject to side constraints. Servicing a customer could involve either picking up or delivering a product, but not both. The side constraints can be the service capacity of the model vehicle, vehicle range, customer demands, or customer service times. Each tour must start and end at the same depot. The objective is to find a set of minimal cost tours that service all customers without violating any side constraints. Like the TSP, there are several extensions to the VRP. Extensions to this basic problem include Capacitated Vehicle Routing Problem (CVRP), Multiple Depot VRP (MDVRP), and VRP with Time Window (VRPTW). Carlton (1995) creates a hierarchical classification scheme for the General VRP (GVRP). Figure 2-1 demonstrates the tier for the TSP, VRP, and pickup and delivery problems (PDP). In a VRP, the vehicles perform either delivery or pickup operations exclusively. A PDP extends the VRP so that vehicles can make one or more pickups from customers along the route for delivery to other customers.

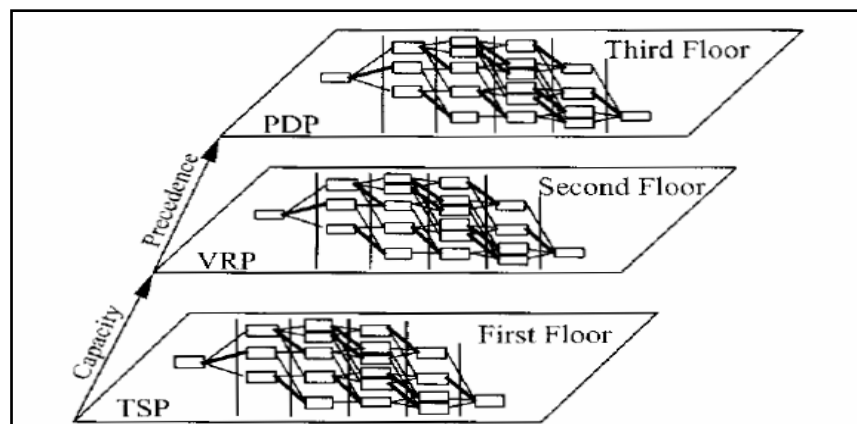


Figure 2-1 GVRP hierarchical classification scheme (Carlton, 1995)

2.5 Crew Scheduling Problem (CSP)

The CSP concerns assigning crew duties to legs (or trips) with the objective of minimizing the crew cost. This CSP can be expressed in formulaic fashion as follows. Let's assume n legs L_1, \dots, L_n have to be covered by a set of crews. Each leg L_j requires uninterrupted driving from a starting point at a given starting time s_j to an ending point at a given ending time $e_j \geq s_j$, and has a weight $w_j \geq 0$ (usually equal to $e_j - s_j$). In addition, a working-time limit is specified. An ordered leg pair (L_i, L_j) is called *infeasible* if the same crew cannot cover L_j immediately after L_i , for example because $e_j > s_j$; otherwise, it is called *feasible*. Todd E. Combs discusses the CSP and its variants in perspective of airline crew scheduling problem in his dissertation paper (2002:25). Freling et al deals an integrated approach to vehicle and crew scheduling for an urban mass transit system with a single depot (Freling and others, 2003:63).

2.5.1 Set Partitioning Problem (SPP)

Traditionally a crew scheduling problem is modeled as the set partitioning problem. When every leg must be served by exactly one duty, the problem takes on the set partitioning format. Commonly cited problems having this structure include the crew-scheduling problem in which every flight of an airline must be scheduled by exactly one cockpit crew. The binary integer programming formulation for such a problem is given below:

$$\begin{aligned} \min \quad & \sum_{j=1}^n c_j x_j \\ \text{subject to: } & Ax = e_m, \\ & x_j \in \{0,1\} \text{ for } j = 1, \dots, n \end{aligned} \tag{1}$$

Where e_m is a vector of m ones, and n is the number of duties that we consider. Each row of the $m \times n$ A matrix represents a leg or segment, while each column represents a driver duty with cost c_j for using it. The x_j are zero-one variables associated with each duty, i.e., $x_j=1$ if duty j is executed. The A matrix is generated one column at a time, with $a_{ij}=1$ if leg i is covered by duty j , 0 otherwise. In a set partitioning problem, each member of a given set, $S1$, must be assigned to or partitioned by a member of a second set, $S2$. For the air crew scheduling problem, each member of the set of flights must be assigned to a member of the set of crew duties.

	(0,4,6,9)	(1,5)	(2,7)	(3,8,10)
	↓	↓	↓	↓
Crew 0	1	0	0	0
Crew 1	0	1	0	0
Crew 2	0	0	1	0
Crew 3	0	0	0	1
Flight 4	1	0	0	0
Flight 5	0	1	0	0
Flight 6	1	0	0	0
Flight 7	0	0	1	0
Flight 8	0	0	0	1
Flight 9	1	0	0	0
Flight 10	0	0	0	1

Figure 2-2 Mapping a CSP solution to the SPP (Combs, 2002)

The CSP provides a natural partitioning of the flights. Each flight is placed in exactly one crew duty, which represents a crew and the flights they fly in a given period of time. These disjoint duties have a one-to-one correspondence with the columns of the set partitioning problem's constraint matrix, as seen in Figure 2-2. The disjoint duties also represent a partial solution to the CSP, i.e., (0, 4, 6, 9) in Figure 2-2 is one crew duty

within the solution set of crew duties. Todd E. Combs also discusses the SPP from a historical perspective (2002:28).

2.5.2 Set Covering Problem (SCP)

In this section a mathematical formulation for the CSP is given. In the set covering formulation of the CSP, the objective is to select a minimum cost set of feasible duties such that each task is included in at least one of these duties. This is the following 0-1 linear program:

$$\begin{aligned}
 & \min \sum_{j=1}^n c_j x_j \\
 & \text{subject to: } Ax \geq e_m, \\
 & \quad x_j \in \{0,1\} \text{ for } j = 1, \dots, n
 \end{aligned} \tag{2}$$

As the reader could see from the above formulation, the equations in SPP are replaced by inequalities. The advantage of working with this formulation instead of a set partitioning one is that it is easier to solve. After solving the set covering formulation, the solution can be always changed into a set partitioning solution by deleting over-covers of legs. In fact, this may be resolved by merely changing some of the selected duties. Instead of being the driver, the person who is assigned to such a duty will stay at LRS for the unscheduled job. Note that such changes affect neither the feasibility nor the cost of the duties involved.

It is well known that the SCP is NP-complete (Beasley, 1990:151) and a number of optimal algorithms have been proposed in the literature for the exact solution of SCP (see Balas and Ho 1980, Beasley 1987, Fisher and Kedia 1990, Beasley and Jörnsten

1992, Nobili and Sassano 1992, and Balas and Carrera 1996). These exact algorithms can solve instances with up to a few hundred rows and a few thousand columns. When larger scale SCP instances are tackled, heuristic algorithms are needed. Classical greedy algorithms are very fast in practice, but typically do not provide high quality solutions, as reported in Balas and Ho (1980) and Balas and Carrera (1996). The most effective heuristic approaches to SCP are those based on Lagrangian relaxation with sub gradient optimization, following the seminal work by Balas and Ho (1980), and then the improvements by Beasley (1990), Fisher and Kedia (1990), Balas and Carrera (1996), and Ceria et al. (1995). Lorena and Lopes (1994) propose an analogous approach based on surrogate relaxation. Wedelin (1995) proposes a general heuristic algorithm for integer programs having a 0-1 constraint matrix; the algorithm is based on Lagrangian relaxation with coordinate search, where a suitably-defined approximation term is introduced. Recently, Beasley and Chu (1996) proposed an effective genetic algorithm.

2.6 Integration of Vehicle Routing and Crew Scheduling

Although in the early 1980s several researchers recognized the need to integrate vehicle and crew scheduling for an urban mass transit system, most of the algorithms published in the literature still follow the sequential approach in which vehicles are scheduled before, and independently of, crews. Algorithms incorporated into commercially successful computer packages use this sequential approach as well, while sometimes integration is dealt with at the user level. In the operations research literature, only a few publications make a comparison/contrast between simultaneous and sequential scheduling.

The traditional sequential strategy is strongly criticized by Bodin et al. (Bodin, 1983). This is motivated by the fact that in North American mass transit organizations the crew costs far out weigh vehicle operating costs, and in some cases reach as high as 80% of total operating costs. Although simultaneous vehicle and crew scheduling is of significant practical interest, only a few approaches of this kind have been proposed in the literature. They mainly deal with bus and driver scheduling and fall into one of the following three categories (Freling and others, 2003:65):

- Scheduling of vehicles as part of a heuristic approach to crew scheduling
- Inclusion of crew consideration in the vehicle scheduling process; the actual crew scheduling is carried out afterwards.
- Complete integration of vehicle and crew scheduling

2.7 Programming Languages

To implement any heuristics or rule-based algorithms, programming languages must be considered. To select the right programming language, considerations of the selection must be based on their availability as well as being easy to learn and use. The majority of the desktop computers in the scheduling division use a version of the Microsoft Windows operating system. “Since Microsoft also develops the MS Office Suite on the foundation of Visual Basic engine, they can build enhancements and attachment modules into the application to solve specific problems, and is assured a very high probability of error free integration” (Nguyen, 2002:21).

MS office products such as Access, Word, and Excel have become the main word processor, database and spreadsheet in the majority of offices and homes. The required software is already present in the office documents because these come already pre-installed with the computers when they are first purchased. 48th LRS scheduling division used to generate and publish the schedules with MS Excel spreadsheet. Visual Basic is used for these compelling reasons over Java and other object oriented programming languages.

In VBA, the attributes of an object are called *properties*: e.g. the size and color of an object. In addition, each property has a *value* associated with it. For example, a car might be white and it may have four doors. In contrast, the things can be done to an object are called *methods*: the drive method and the park method, for example. Methods can take qualifiers, called *arguments*, which indicate how a method is carried out (Albright, 2001:7).

Some of the most common objects in Excel are ranges, worksheets, charts and workbooks. For example, consider the single-cell range B5. This range is considered a Range object. It has a Value property: the value (either text or numeric) in the cell. A Range object also has methods. For example, a range can be copied. The Copy method takes the destination as its argument.

There is an object hierarchy in Microsoft Excel Objects. At the top of the hierarchy is the Application object. This refers to Excel itself. One step down from application is the Workbooks collection. One step down from Workbook is the Worksheet objects and the other objects follow it (Albright, 2001:8-9).

2.8 Scheduling in the 48th LRS Environment

To help understanding the conceptual assignment flows, Figure 2-3 shows the conceptual map of 48th LRS.

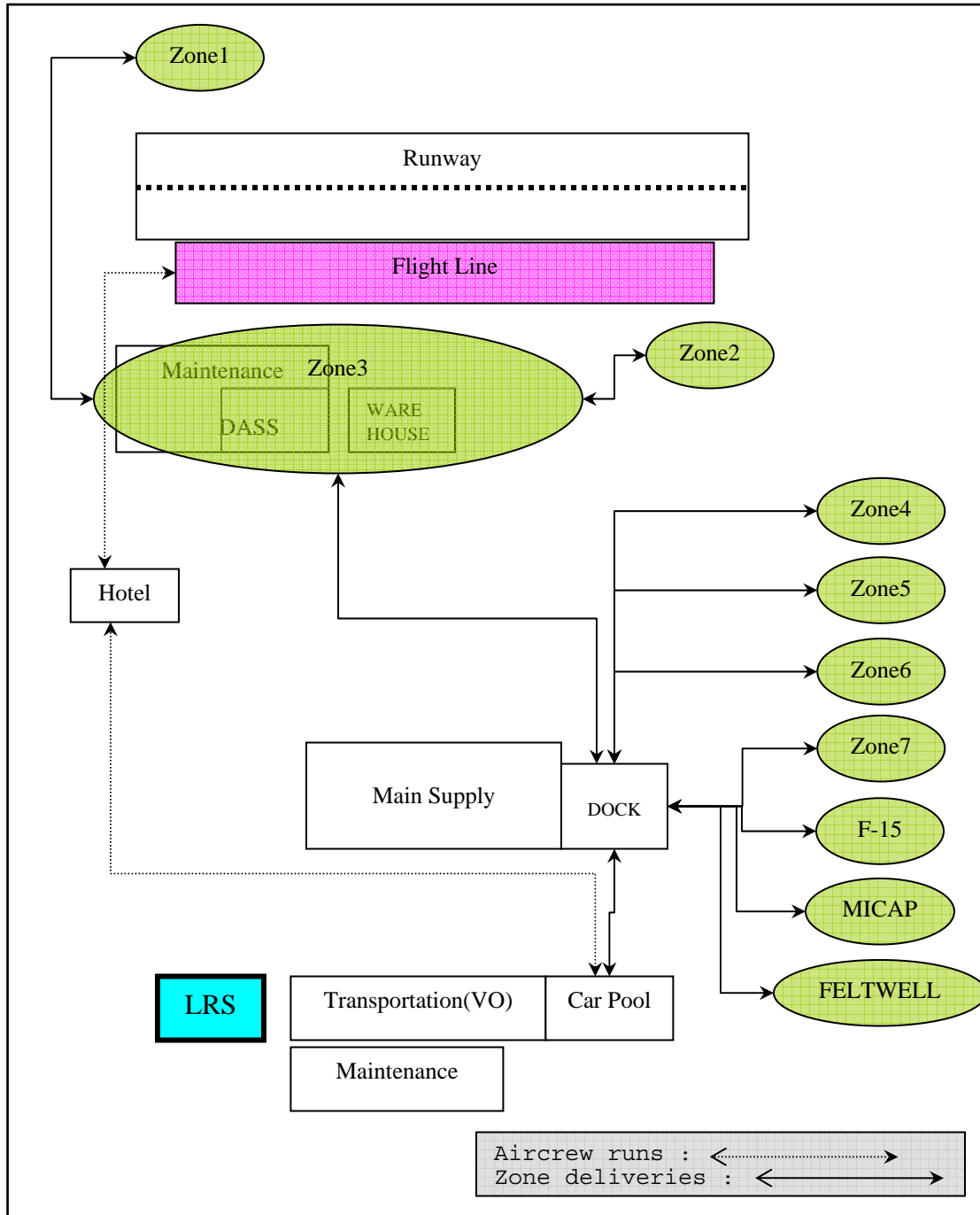


Figure 2-3 Conceptual map of 48th LRS

Throughout this paper, the term “Zone” is used. This term could be thought of as the customer site or leg where pickup and delivery should be done. Zone is not a single site, but a set of many sites to be visited. Figure 2-4 demonstrates the concept of zone, and the route for a vehicle. The individual positions within a zone are not the emphasis of this paper; however, the starting time, ending time, and frequencies of each zone are specified.

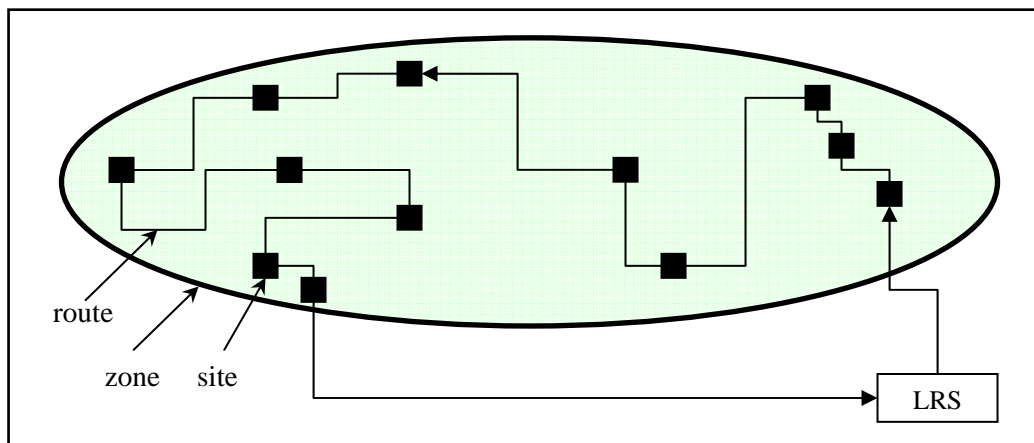


Figure 2-4 Concept of Zone and Sites

Table 2-1 provides the minimum runs which the dispatchers must fulfill and assign operators (drivers) to. Zone 3 is the dedicated aircraft support section (DASS). Usually, DASS is located next to the airway and executes quick repair service and replacement for the aircrafts. Zone 3 is picked up by Zones 1&2 on their sweeps, to ensure the DASS's are being delivered to every hour. FELTWELL receives deliveries twice a week on Tuesday and Thursday, and the delivery start time is 08:00AM. FELTWELL is a little town which is located at the north of Lakenheath Base.

Table 2-1 Minimum Daily Runs (delivery schedule)

Zone	Frequency(daily)	Required time	Delivery start times
Zone 1&2	8 times	2 hrs	8:00AM,10:00AM,12:00PM,14:00PM,16:00PM,18:00PM,20:00PM,22:00PM
Zone 3 (DASS)	8 times	2 hrs	7:00AM,9:00AM,11:00PM,13:00PM,15:00PM,17:00PM,19:00PM,21:00PM
Zone 4&5	2 times	3 hrs	8:00AM, 13:00PM
Zone 6	2 times	3 hrs	Only Tues/Thurs (8:00AM,13:00PM)
Zone 7	2 times	2 hrs	7:00AM,13:00PM
F-15	6 times	3 hrs	
MICAP to RAFM	3 times	3 hrs	8:00AM,14:30PM,22:00PM
FELTWELL	1 time		Only Tues/Thurs

To begin examining the Vehicle Operation Element (VOE) process, a high-level look at the process is needed.

Figure 2-5 shows the VOE scheduling input source representing the VOE scheduling process. The objective of this scheduling process is to minimize cost. Note that the cost is sum of all duties costs (c_j) from SPP or SCP. To minimize the cost could be understood to mean to minimize the number of drivers or the number of duties needed for accomplishing the customer's requests. The main output of the element scheduling shop is the daily schedule. Information about availability of vehicles is taken from the maintenance element. The dispatcher determines when an operator runs a mission, with what type of vehicle, and where to go. The dispatchers review the scheduled runs for the next day and prioritize the requests. They concentrate on the daily recurring runs.

However, there are also intermittent recurring runs such as unscheduled pick up and delivery (P&D), vehicle maintenance support, command car servicing, transient air crew delivery, and so on. Then they look to see which available operators are scheduled for that time period and assign them to the runs according to their qualifications. The LRS transports an average of 50 classified items per week. Additionally, they make

approximately 15-20 MICAP runs per week. Unfortunately, Ministry of Defense (MoD) personnel and DoD personnel cannot transport “classified” property, and this reduces the pool of available LRS drivers. This issue introduces a little complexity regarding scheduling; however, this could not be overlooked as it is the most important consideration. Appendix A shows one example of daily recurring requests for military personnel and civilian personnel.

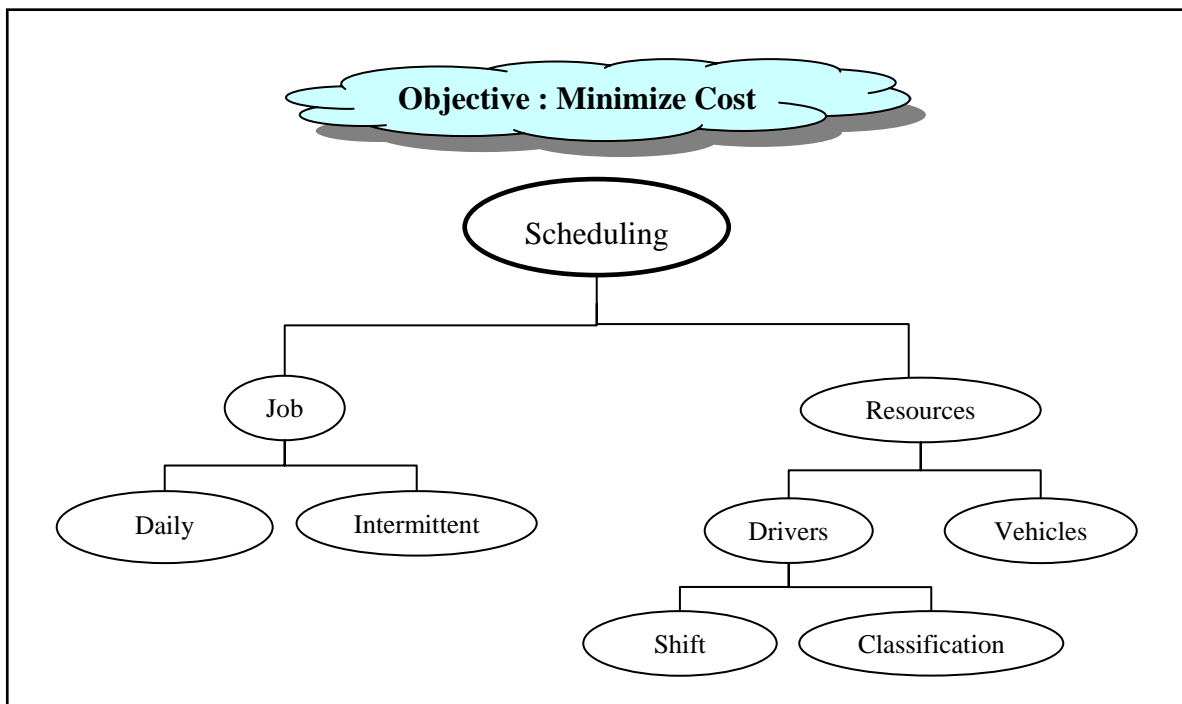


Figure 2-5 VOE Scheduling Input Sources

2.9 Implementation issue

This section explains how the LRS problem could be solved by applying the theories discussed in the previous sections. Most important idea is to use reasonable programming language for the schedule and to implement the concept of SCP already covered in the previous section. Currently, the dispatchers in the VOE do not use any

computer package tool or scheduling model. Depending on the manual approach to the dynamic environment does not guarantee any efficient solution. Dispatchers may well be able to make a feasible schedule, but there is no effective means to measure how their schedule is good or to find more compatible schedules. A model based on VBA could enhance their capability for making good schedules and provide the scheduler with a more flexible plan to create a dynamic scheduling environment.

It is very reasonable to find some analogy between SCP and the LRS's scheduling environments to advance the research. Under current protocol, every leg (or trip) must be covered exactly once at a scheduled time (SPP). When the 'exactly once' constraint is relaxed, the problem is reduced to the SCP. If a schedule gets some over-cover legs, then the extra legs which don't need to be done could be reassigned to other assignments. In some sense, the over-cover legs provide more flexibility to the scheduler. For instance, if one driver were freed from responsibility for a leg, then he/she could be assigned to other tasks (e.g. emergency delivery, washing vehicles, etc).

2.10 Excel Solver

Solver is part of a suite of commands sometimes called what-if analysis tools. What-if analysis is a process of changing the values in cells to see how those changes affect the outcome of formulas on the worksheet, for example, the user might vary the interest rate that is used in an amortization table to determine the amount of the payments. With Solver, the user can find an optimal value for a formula in one cell—called the target cell—on a worksheet. A formula is a sequence of values, cell references, names, functions, or mathematical operators in a cell that together produce a

new value. Solver works with a group of cells that are related, either directly or indirectly, to the formula in the target cell. Solver adjusts the values in the changing cells— called the adjustable cells— specified by the user to produce a user specified result in the target cell formula (usually maximization or minimization). The user can apply constraints which are the limitations placed on a Solver problem. The user can apply constraints to adjustable cells, the target cell, or other cells that are directly or indirectly related to the target cell to restrict the values Solver can use in the model. The constraints can also refer to other cells that affect the target cell formula. Solver determines the maximum or minimum value of one cell by changing other cells. For example, the user can change the amount of a projected advertising budget and see the affect on the projected profit amount.

The Microsoft Excel[®] Solver tool uses the Generalized Reduced Gradient (GRG2) nonlinear optimization code developed by Leon Lasdon, University of Texas at Austin, and Allan Warren, Cleveland State University. Integer problems use this method and the branch-and-bound method, implemented by John Watson and Dan Fylstra, Frontline Systems, Inc.

2.10.1 Reduced Cost

Consider the following linear programming problem:

$$\begin{aligned} \text{Minimize } & \mathbf{cx} \\ \text{Subject to } & \mathbf{Ax} = \mathbf{b} \\ & \mathbf{x} \geq \mathbf{0} \end{aligned} \tag{3}$$

Where A is an $m \times n$ matrix with rank m . Suppose that we have a basic feasible solution

$\begin{pmatrix} B^{-1}b \\ \mathbf{0} \end{pmatrix}$ whose objective value z_0 is given by

$$z_0 = c \begin{pmatrix} B^{-1}b \\ \mathbf{0} \end{pmatrix} = (c_B, c_N) \begin{pmatrix} B^{-1}b \\ \mathbf{0} \end{pmatrix} = c_B B^{-1}b \quad (3.1)$$

Now let x_B and x_N denote the set of basic and nonbasic variables for the given basis.

Then feasibility requires that $x_B \geq \mathbf{0}$, $x_N \geq \mathbf{0}$, and that $b = Ax = Bx_B + Nx_N$.

Multiplying the last equation by B^{-1} and rearranging the terms, we get

$$\begin{aligned} x_B &= B^{-1}b - B^{-1}Nx_N \\ &= B^{-1}b - \sum_{j \in R} B^{-1}a_j x_j \\ &= \bar{b} - \sum_{j \in R} (y_j) x_j, \text{ say,} \end{aligned} \quad (3.2)$$

Where R is the current set of the indices of the nonbasic variables. Noting Equations

(3.2) and (3.1) and letting z denote the objective function value, we get

$$\begin{aligned} z &= cx \\ &= c_B x_B + c_N x_N \\ &= c_B (B^{-1}b - \sum_{j \in R} B^{-1}a_j x_j) + \sum_{j \in R} c_j x_j \\ &= z_0 - \sum_{j \in R} (z_j - c_j) x_j \end{aligned} \quad (3.3)$$

Where $z_j = c_B B^{-1}a_j$ and $y_j = B^{-1}a_j$ for each nonbasic variable.

Using the foregoing transformations, the linear programming problem LP may be rewritten as

$$\begin{aligned}
& \text{Minimize} && z = z_0 - \sum_{j \in R} (z_j - c_j)x_j \\
& \text{Subject to} && \sum_{j \in R} (y_j)x_j + x_B = \bar{b} \\
& && x_j \geq 0, \ j \in R, \text{ and } x_B \geq 0
\end{aligned} \tag{4}$$

The values $(c_j - z_j)$ are sometimes referred to as reduced cost coefficients since they are the coefficients of the non basic variables in this reduced space. The key result simply says the following: If $(z_j - c_j) \leq 0$ for all $j \in R$, then the current basic feasible solution is optimal. This should be clear by noting that since $z_j - c_j \leq 0$ for all $j \in R$, we have $z \geq z_0$ for any feasible solution, and for the current basic feasible solution, we know that $z = z_0$ since $x_j=0$ for all $j \in R$. (Bazaraa, 1990:93)

For any non basic variable, the reduced cost for the variable is the amount by which the non basic variable's objective function coefficient must be improved before that variable will become a basic variable in some optimal solution to the LP. (Winston, 2004:253)

2.10.2 Shadow Price

The shadow price of the i^{th} constraint of a linear programming problem is the amount by which the optimal z -value is improved if the right-hand side of the i^{th} constraint is increased by 1 (assuming that the current basis remains optimal). If the right-hand side of the i^{th} constraint is increased by Δb_i , then (assuming the current basis remains optimal) the new optimal z -value for a problem may be found as follows:

- Maximization problem : $z_{opt(new)} = z_{opt(old)} + w_i \times \Delta b_i$
- Minimization problem : $z_{opt(new)} = z_{opt(old)} - w_i \times \Delta b_i$

Where, $z_{opt(new)}$ is new optimal z-value, $z_{opt(old)}$ = old optimal z-value, and w_i is constraint i 's shadow price (Winston, 2004:252).

For a maximization LP, the shadow price of the i^{th} constraint is the value of the i th dual variable in the optimal dual solution. For a minimization LP, the shadow price of the i th constraint = $-(i$ th dual variable in the optimal dual solution). A \geq constraint will have a nonpositive shadow price; a \leq constraint will have a nonnegative shadow price; and an equality constraint may have a positive, negative, or zero shadow price. (Winston, 2004:344)

2.11 Heuristic (Simulated Annealing)

“A heuristic is a technique which seeks good (i.e. near optimal) solutions at a reasonably computational cost without being able to guarantee either feasibility or optimality, or even in many cases how close to optimality a particular feasible solution is.” (Reeves, 1995:6). Heuristics are a subset of algorithms. Therefore it is important to define the location of heuristics within the system of algorithms. Algorithms are the procedures used for solving a problem stated in mathematical terms.

Most algorithms work iteratively, i.e. certain procedures are repeated several times. Iterative algorithms may not necessarily converge towards the sought solution. These are the algorithms, which will be called Heuristics. Even if the uncounted numbers of iterative algorithms differ from each other in many details, a general structure can be shown which represents the vast majority of the iterative algorithms, if not all (Muller-Merbach, 1981:6-8).

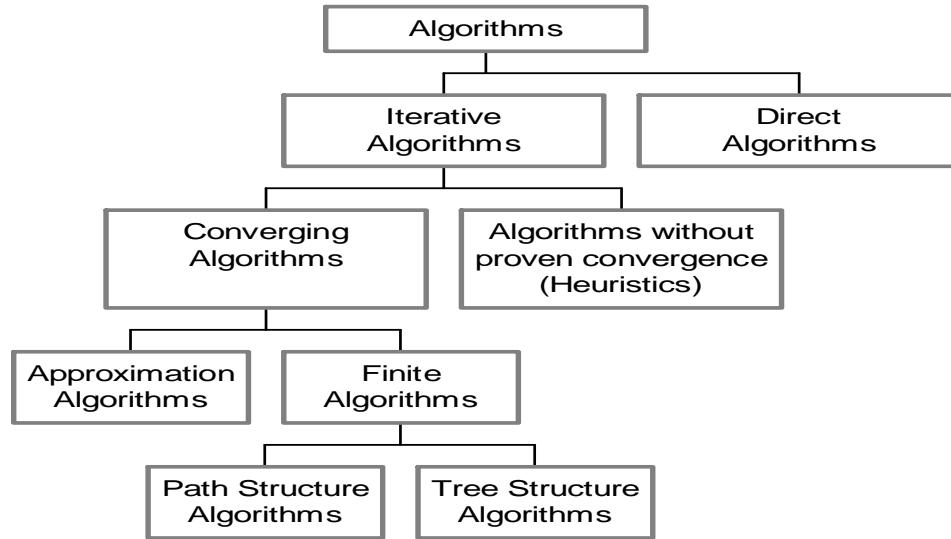


Figure 2-6 Tree with System of Algorithms (Muller-Merbach, 1981:6-8)

In terms of computational complexity, the SCP belongs to the class NP-hard in the strong sense. A polynomial-time algorithm does not exist for members of this class. The number of possible solutions to the SCP grows exponentially as the number of duties (or sets) increases. Throughout this research, the Simulated Annealing (SA) heuristic will be implemented. Heuristic approaches provide no guarantee of optimality, although most provide at least a feasible solution in a relatively short amount of time. Timeliness of a solution is very important for our implementation, as LRS operations are typically time-sensitive.

SA is a local search inspired by the process of annealing in physics (Kirkpatrick et al., 1983). It is widely used to solve combinatorial optimization problems, especially to avoid becoming trapped in local optima when using simpler local search methods (Aarts et al., 1997). This is done as follows: an improving move is always accepted while a worsening one is accepted according to a probability which depends on the amount of deterioration in the evaluation function value. In other words, the less successful a move

is demonstrated to be, the less likely it is to be accepted. Formally a move is accepted according to the following probability distribution, dependent on a virtual temperature T , known as the Metropolis distribution:

$$p_{accept}(T, s, s') = \begin{cases} 1 & \text{if } f(s') \leq f(s) \\ e^{-\frac{(f(s') - f(s))}{T}} & \text{otherwise} \end{cases}$$

Where s is the current solution, s' is the neighbor solution and $f(s)$ is the evaluation function. The temperature parameter T , which controls the acceptance probability, is allowed to vary over the course of the search process. Figure 2-7 shows its basic structure.

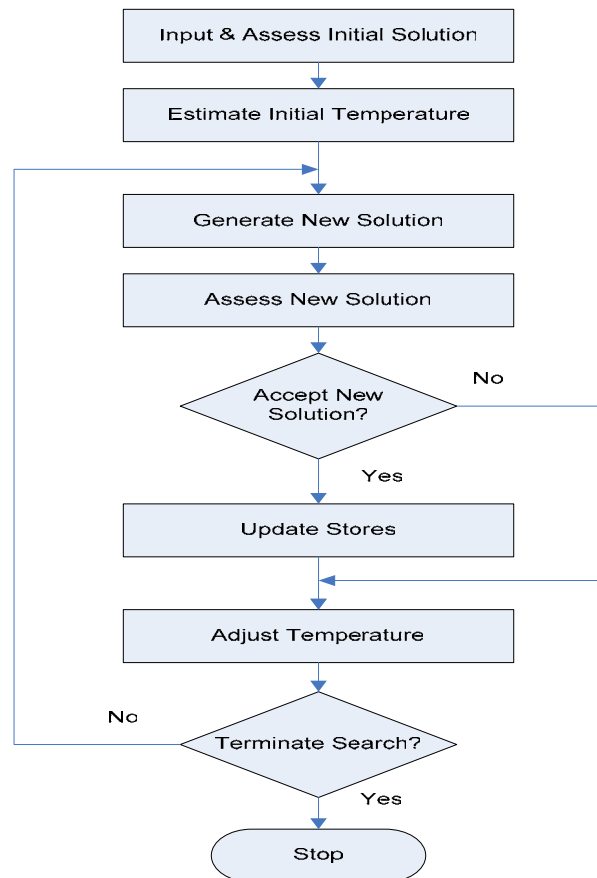


Figure 2-7 Structure of Simulated Annealing Algorithm

The implementation of the SA algorithm is remarkably easy and the following elements must be provided. The details will be explained in next chapter.

- A representation of possible solutions
- A generator of random changes in solutions
- A means of evaluating the problem functions, and
- An annealing schedule – an initial temperature and rules for lowering it as the search progresses.

2.12 Summary

This chapter has presented an overview of the scheduling theory and related topics. In addition to a review of the pertinent literature on scheduling, this chapter has also provided the background of the scheduling environment of 48th LRS and heuristic approach. Chapter 3 presents the methodology for solving the squadron scheduling problem.

Chapter 3. Methodology

3.1 Chapter Overview

This chapter describes the methodology to be employed in the thesis. This chapter is partitioned into three distinct areas: assumptions, scheduling goals and objectives, the scheduling model and problem characteristics. Scheduling details will be covered in the section dealing with the scheduling model and problem characteristics.

3.2 Assumptions

Generally, assumptions are a critical aspect of solving problems. To develop the LRS Daily Squadron Scheduler (DSS), several assumptions should be considered.

- one day time horizon
- no limitation for quantity of vehicles availability
- vehicle routing already accomplished

First, crew assignments are assumed to start and end at the same home base, LRS. This is a natural assumption for short-term pickup and delivery jobs. The Vehicle Operation Element (VOE) in the LRS is charged with a wide variety of tasks. However, the vehicle and crew schedule has a time horizon of length equal to 1. The schedule is assumed to be repeated daily.

Second, there is no limitation for vehicle availability (Rodney L. Mills. F_Flight Commander, 48th LRS, Lakenheath AFB. Telephone interview. 4 August 2004). This assumption implies that only human availability influences the schedules. Generally, scheduling problems are constrained by both vehicle and crew limitations. With no

consideration given to the availability of, this research will focus solely on the crew scheduling portion.

Third, vehicle routing is already done. In a vehicle routing problem, a single vehicle must visit a set of customers exactly once and then return home. Figure 3-1 shows the structure of 48th LRS crew scheduling problem. The vehicle routes have already been completed by the LRS and have been defined as zones in our research. Each vehicle will travel to a zone and return back to the original depot, and this process will continue until one driver completes his/her mission for the day.

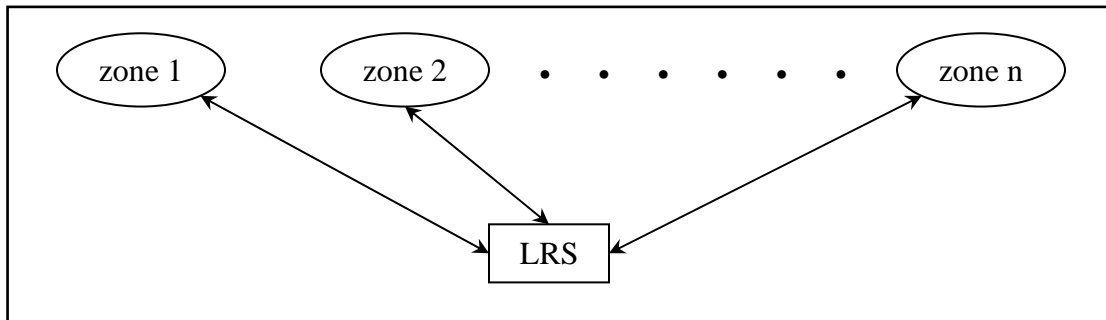


Figure 3-1 LRS crew scheduling structure

3.3 Scheduling Goals and Objectives

The squadron schedulers at LRS produce the daily vehicle scheduling to meet certain goals. The schedules need to satisfy the necessary pick-up and delivery service throughout the day. Due to a shortage of drivers and a lack of efficient scheduling tools, some customers' requests may not be accomplished during the day. The scheduler should balance the workload among the assigned squadron drivers based on squadron policy. An evenly distributed workload is a critical factor in good scheduling.

The overall objective for the VOE scheduler is to establish a robust schedule that will both satisfy customer service demands and distribute work loads in a balanced manner. The objective of this thesis is to provide a scheduling tool that is flexible, quick, easy to use, and conducive to an optimal daily schedule.

3.4 Scheduling Model and Problem Characteristics

In order to understand the scheduling model, one must begin with an overview of the scheduling process. The scheduling process in DSS can be summarized by the following 5 steps.

1. Receive the daily recurring jobs and intermittent recurring jobs
2. Prioritize the jobs / check the availability of drivers and their qualification
3. Set up parameters for preparatory processing
4. Generate eligible duties
5. Generate a schedule

To produce a robust schedule, the scheduling environment has to be understood in terms of its dynamic changes, scheduling requirements and other scheduling related constraints. The operation environment at the 48th LRS is a fluid and dynamic environment characterized by daily changing requirements. Requirements and priority changes to schedules occur frequently, and this initiates a modification of the schedules. For example, a driver might become ill and if there is no suitable substitute for the driver, the schedule change is inevitable and may not accomplish certain customers' requests.

3.5 Receive the daily recurring jobs and intermittent recurring jobs

A leg could be a zone, set of zones, or job a vehicle serves. In this research, each customer or job corresponds to a leg. Legs are categorized by several elements such as recurring period, classification, assignment taker, etc. Depending on the recurring period, legs could be grouped into two jobs. One is the daily recurring legs and the other is the intermittent recurring legs. Table 3-1 shows the category and the entities of each category. For the classification elements, 0-1 coding scheme is implemented, which is 1 for classified legs and 0 for non-classified legs. Classified legs should be performed by military personnel with 2T1X1 specialty. The assignment taker elements distinguish the military and civilian legs. Military personnel can perform the civilian legs, but not vice versa.

Table 3-1 Category of Leg

Daily Recurring Legs		Intermittent Recurring Legs
P&D	Zone 1&2	Unscheduled P&D
	Zone 3	
	Zone 4&5	
	Zone 6	
	Zone 7	
Aircrews(days/nights)		Vehicle Maintenance Support
Shuttle		Command Car Servicing
MICAP		Transient Aircrew
Non-Milstrip		

Each leg has fixed starting and ending times, and the traveling times between all pairs of locations are known. The daily recurring legs are the ones which should be covered routinely every day or night. Exceptionally, there are some specific legs covered

only every Tuesday and Thursday only. However, the intermittent recurring legs are unpredictable trips that may or may not result in changes in a predetermined schedule.

3.5.1 Daily recurring jobs

Responsibilities for Military Personnel (2T1X1)											
No	CustomerID	Start	End	LENGTH	Possible next start(earliest)	Possible next start(latest)	Vehicle type	Classified	Mil/Civ	Priority	App
1	REDBALL/in-out check	7:00	15:00	8:00	15:00	16:00	1.5ton	1	M	1	0
2	zone 3	7:00	9:00	2:00	9:00	10:00	1.5ton	1	M	1	0
3	zone 3	9:00	11:00	2:00	11:00	12:00	1.5ton	1	M	1	0
4	zone 3	13:00	15:00	2:00	15:00	16:00	1.5ton	1	M	1	0
5	training(trainer)	7:00	15:00	8:00	15:00	16:00	1.5ton	1	M	1	0
6	training(trainer)	7:00	15:00	8:00	15:00	16:00	1.5ton	1	M	1	0
7	training(trainee)	7:00	15:00	8:00	15:00	16:00	1.5ton	0	M	1	0
8	training(trainee)	7:00	15:00	8:00	15:00	16:00	1.5ton	0	M	1	0
9	veh servicing	7:00	11:00	4:00	11:00	12:00	1.5ton	0	M	1	0
10	veh servicing	7:00	10:00	3:00	10:00	11:00	1.5ton	0	M	1	0
11	zone3	11:00	13:00	2:00	13:00	14:00	1.5ton	1	M	1	0
12	zone 1/2(zone 3)	12:00	14:00	2:00	14:00	15:00	1.5ton	1	M	1	0
13	RAFM MICAP	8:00	11:00	3:00	11:00	12:00	tractor	1	M	1	0
14	RAFM MICAP	14:00	17:00	3:00	17:00	18:00	tractor	1	M	1	0
15	zone 7	7:00	9:00	2:00	9:00	10:00	1ton	1	M	1	0
16	zone 7	13:00	15:00	2:00	15:00	16:00	1ton	1	M	1	0
17	zone 1/2(zone 3)	8:00	10:00	2:00	10:00	11:00	1.5ton	1	M	1	0
18	zone 1/2(zone 3)	10:00	12:00	2:00	12:00	13:00	1.5ton	1	M	1	0
19	zone 1/2(zone 3)	14:00	16:00	2:00	16:00	17:00	1.5ton	1	M	1	0
20	zone 3	15:00	18:00	3:00	18:00	19:00	1.5ton	1	M	1	0
21	zone 1/2(zone 3)	16:00	18:00	2:00	18:00	19:00	1.5ton	1	M	1	0
22	zone 3	17:00	19:00	2:00	19:00	20:00	1.5ton	1	M	1	0
23	REDBALL/in-out check	16:00	0:00	8:00	0:00	1:00	1.5ton	1	M	1	0
24	zone 1/2(zone 3)	18:00	20:00	2:00	20:00	21:00	1.5ton	1	M	1	0
25	zone 1/2(zone 3)	20:00	22:00	2:00	22:00	23:00	1.5ton	1	M	1	0
26	zone 1/2(zone 3)	22:00	0:00	2:00	0:00	1:00	1.5ton	1	M	1	0
27	zone 3	19:00	21:00	2:00	21:00	22:00	1.5ton	1	M	1	0
28	zone 3	21:00	23:00	2:00	23:00	0:00	1.5ton	1	M	1	0
29	RAFM MICAP	22:00	1:00	3:00	1:00	2:00	tractor	1	M	1	0
30	MID SHIFT	19:00	7:00	12:00	7:00	8:00	1.5ton	1	M	1	0

Figure 3-2 Daily recurring jobs

Figure 3-2 demonstrates military responsibilities of VOE's daily recurring jobs which are covered by vehicles in the LRS. Recall a "Zone" is a set of various sites to visit. For instance, zone 3 has a start time of 7:30 and an end time of 9:30. During the two-hour service time, the vehicle could travel to 1, 2 or more sites which are covered by zone 3. The following explains the terms in Figure 3-2.

- CustomerID: this is a designated set of sites to visit, and each one would be regarded as a leg. This includes the physical place and all kind of jobs to be done (e.g. redball, training, vehicle servicing, etc.)
- Start: this is the time when service starts. "Service starts" means the sweep process is initiated. The Sweep process is summarized as follows: 1) the driver

scans the property with the Supply Asset Tracking System (SATS) gun and loads the property from the warehouse into the delivery vehicle. 2) the driver travels to the delivery destination of property. 3) upon arrival at the destination, the driver will find a “smart card” holder to sign for the property electronically with SATS.

- End: this is the time when service terminates and the driver is back at the depot.
- Length: this is service duration.
- Possible next start (earliest): this is the time considering the minimum rest time.
- Possible next start (latest): this is the time considering the maximum rest time.
- Vehicle type: in this thesis, we consider 5_types of vehicles (1ton, 1.5ton, tractor, 19pax, 39pax), and there is no vehicle shortage for the duties.
- Classified: classified requirement - 1, otherwise – 0
- Mil/Civ: military or civilian driver requirement
- Priority: prioritization of customers according to specific criteria (index from 1 to 3)
- Appointment: this is job status designation as “Regular” or “Appointment”

3.5.2 Intermittent recurring jobs

Currently VOE has total of 49 daily recurring legs (military-30 legs and civilian-19 legs). The LRS scheduler receives various intermittent jobs for the next day from various customers. A spreadsheet is built to record both daily recurring jobs and intermittent recurring jobs. Whenever the scheduler initiates this model, a baseline data is cut and pasted into a designated sheet. Using a self-defined input customer data form (Figure 3-3), intermittent recurring jobs are located at the bottom of the baseline data.

The screenshot shows a window titled "Input Customer data" with a close button (X) in the top right corner. The window contains the following elements:

- CustomerID:** A text input field.
- Demanded Vehicle:** A dropdown menu.
- Start Time:** A dropdown menu.
- End Time:** A dropdown menu.
- Classified:** A dropdown menu.
- Military / Civilian:** A dropdown menu.
- Priority:** A dropdown menu.
- Job status:** A dropdown menu.
- Buttons:** Three buttons are located on the right side: "Insert", "Reset", and "Finish".

Figure 3-3 Input Customer data (intermittent legs)

3.6 Prioritize the jobs

The primary goal of LRS is to maximize the satisfaction of all the units' demands under his service scope. To maximize does not always mean to accomplish all the services demanded by customers. In the best of circumstances, all the customer demands can be met despite restrictions on drivers. However, in reality, this is quite uncommon. When the schedulers cannot reach a feasible solution with the resources available to them, they usually prioritize some jobs over others. If certain jobs have a lower priority index, then they will be penalized. DSS will implement the priority process via several steps. Before running the scheduling process, the user puts the priority index at the end of the customer data: a lower index for example, ("1") is an important job and higher index ("3") is a less important job. Less important does not mean that the job is not important. However, it is a job which could be taken out of consideration when the scheduler cannot find a feasible solution to cover all jobs.

A Schedule result type has two options: 1) find the minimum number necessary drivers, 2) find possible jobs with available drivers. The priority is associated with the second option. Details will be covered at section 3.9.1 (Pricing Approach).

3.7 Check the availability of drivers and their qualification

The scheduler needs to keep track of available number of drivers and their qualifications. Naturally, the status of a driver will have an impact on the next day's schedule. A driver might have a two-hour appointment with a doctor or might be on leave. Those are predictable and the tracking is controllable things which must be considered before processing the schedule. With this project, a limitation on personal appointments during the shift time will be imposed. Each driver can have at most one private appointment (e.g. dentist appointment or pick-up children, etc) under persuasive document proof. DSS will process that appointment in the same fashion as regular legs.

3.8 Preparatory processing (parameter set-up)

Parameter setting is a prerequisite procedure for duty generation. It determines which schedule strategy the scheduler will implement. Using the given parameters, DSS will provide some insights about the schedule environment, such as lower bound of necessary crew numbers or the best schedule scheme, etc.

The screenshot shows the '48th LRS Daily Squadron Scheduler' window. It contains two main sections: 'Parameters' and 'Schedule Result Type'.

Parameters Section:

- Number of Shifts:** A spinner box set to 4.
- Shift:** A table with 4 columns (1, 2, 3, 4) and 2 rows (Start Time, End Time). Each cell contains a spinner box.
- Meal Break:** A table with 3 columns (Shift1Meal, Shift2Meal, Shift3Meal) and 2 rows (Start Time, End Time). Each cell contains a spinner box. Shift2Meal Start Time is set to 11:30 and Shift2Meal End Time is set to 13:30.
- Min sit (minutes):** A spinner box set to 0.
- Max sit (minutes):** A spinner box set to 0.
- Min workload (minutes):** A spinner box set to 0.
- Max workload (minutes):** A spinner box set to 0.
- Schedule:** A dropdown menu set to 'Military'.

Schedule Result Type Section:

- Find necessary minimum number of drivers:** An unselected radio button.
- Find possible jobs with available drivers:** A selected radio button.
- shift1:** A label above a spinner box set to 0.
- Military:** A label above a spinner box set to 0.

At the bottom right, there are three buttons: 'Finish', 'Reset', and 'Cancel'.

Figure 3-4 Parameter setting procedure screenshot

The *Number of shifts* box helps the scheduler to compare several shift strategies. In reality, the LRS operates under a two-shift or three-shift scheme. However, the ability to utilize one and four shifts will provide more flexibility to the scheduler in a specific situation. DSS allows for up to 4 shifts. When the scheduler sets one shift, DSS will result in the best schedule (or lower bound) with the specific setting of *Min/Max sit* and *Min/Max workload*. One shift is also categorized into two types of one shift; a self defined completed shift and an uncompleted shift. The completed shift implies the start time of the shift is same as the end time of the shift. The uncompleted shift implies the start time and end time do not match.

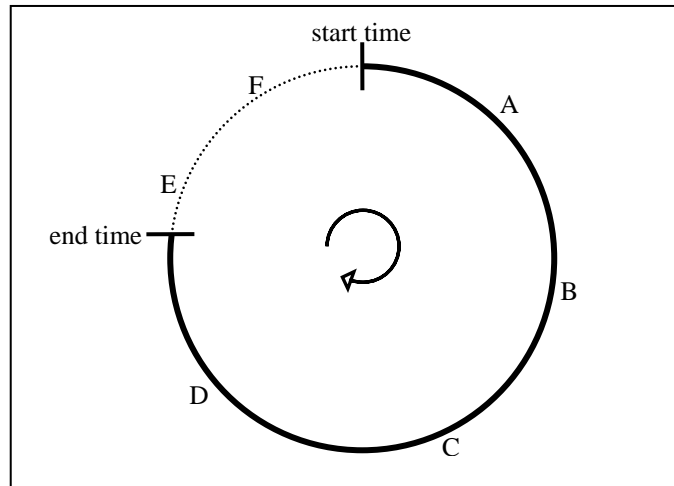


Figure 3-5 Example of One Shift Timeline (uncompleted)

Figure 3-5 demonstrates an example of an uncompleted one shift timeline. A, B, ..., F is a potential point of leg start or end time. Any leg which starts or ends between end time and start time will be excluded from consideration, as will any leg which cross the [end time – start time] zone (e.g., D – A). The set of $\{(A - B), (A - C), (A - D), (B - C), (B - D), (C - D)\}$ are feasible legs. This kind of uncompleted shift concept is unusual in a real situation. It is worthwhile to consider an imaginary schedule environment such as a training period lasting several hours when all military personnel are prohibited from driving vehicles.

In the case of the multi-shifts scheme, the issue of a shift separator between legs arises. It sounds simple, but there is a problem when a leg starts on one shift and continues through the other shift. With this kind of problem, the balance skill which assigns a leg with more processing time in shift A than shift B to shift A, is implemented. When there is the same amount of processing time in both shifts, then DSS arbitrarily assigns the leg to the later shift.

Min sit and *Max sit* – refer to the minimum and maximum connection time between two consecutive legs in a duty. In reality, the LRS use 0 minutes for *Min sit*. This implies that a driver could start another leg immediately after he or she finishes a previous leg and returns to the depot. The *Min sit* and *Max sit* are not fixed variables. The scheduler could change the values at the planning phase.

The definition of *Min workload* and *Max workload* for a day is intuitive. These workloads exclude the meal break of 60 minutes (breakfast, lunch or dinner).

Throughout this research, the shift1 meal break (breakfast) time is between 5:00am and 7:00am, the shift2 meal break (lunch) time is between 11:30am and 13:30pm, and the shift3 meal break (dinner) time is between 17:30pm and 19:30pm. When the scheduler makes a schedule with 4 shifts (6 hours each), the meal consideration is ignored.

In Figure 3-6, a duty with a workload of 8 hours (480 minutes) is displayed. Each s_i and e_i is a start and end time of *leg i*. Intuitively, one may view this as a feasible duty, but it is not. There is no time slot for a lunch break (assuming the consideration of lunch meal break). The DSS meal break algorithm is based on several assumptions: 1) *Max workload* for a day should not be more than 12 hours. 2) If a leg's workload is greater than 8 hours, the model does not apply meal considerations to the leg. For instance, a "Training" leg is an 8-hour workload and the driver could finish a meal within the 8-hour time slot. 3) Only a complete shift is considered. 4) Though a leg has a late breakfast time and an early lunch time, the leg will have only a one-hour meal break when the model considers both breakfast and lunch breaks.

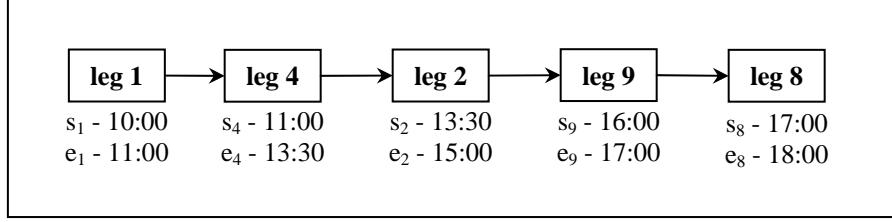


Figure 3-6 Example Duty

DSS will consider the meal break with the following transformation scheme:

- If $11:30\text{am} \leq s_i \leq 13:30\text{pm}$ and $11:30\text{am} \leq e_i \leq 13:30\text{pm}$ then
 $s_i = \text{original } s_i$ and $e_i = e_i + 1 \text{ hour}$
- If $11:30\text{am} \leq s_i \leq 13:30\text{pm}$ then
 $s_i = s_i - 1 \text{ hour}$
Else $s_i = \text{original } s_i$
- If $11:30\text{am} \leq e_i \leq 13:30\text{pm}$ then
 $e_i = e_i + 1 \text{ hour}$
Else $e_i = \text{original } e_i$
- If $11:30\text{am} > s_i$ and $e_i > 13:30\text{pm}$ then
 $e_i = e_i + 1 \text{ hour}$

This transformation changes the original start time, end time and workload of the leg, assuming that the leg is in a specific time window (i.e., 11:30 – 13:30). When a leg starts and ends precisely in the lunchtime window, the condition (1) will extend the end time one hour. The transformation scheme generates notional leg times by adding an hour to one of the legs. During the one-hour slot, the crew could have a meal, and the time is not included in the workload. Breakfast or dinner will be considered in the same fashion.

When a combination of legs is eligible for a duty, it should satisfy the following five time constraints associated with the starting and ending times of each leg. First, there should be no overlap processing time between individual legs in a duty. It is obvious that one driver cannot cover two legs at the same time. Second, the sitting time

between legs should satisfy the *Min sit* and *Max sit* constraints. Third, the total workload of a combination of legs should be within the range of *Min workload* and *Max workload*. Fourth, the meal break between legs should be guaranteed. Finally, only legs in the same shift may be combined into a specific duty.

3.9 Generate Eligible Duties

The tasks that are assigned to the same crew member define a *crew duty*. Together the duties constitute a crew schedule. Duties consist of a number of legs (or tasks) with a given maximum number of legs. In practice, this maximum is very often equal to 2 or 3. In this research we put five legs as the maximum number of legs. In this research, the terms of *one-leg duty*, *two-leg duty*, *three-leg duty*, *four-leg duty*, and *five-leg duty* are defined as a *crew duty* consisting of n legs. The average leg length is approximately 2 hours. Therefore to consider up to 5 legs ($2 \text{ hours} \times 5 \text{ legs} = 10 \text{ hours}$) is reasonable since an 8 hour shift is standard.

A duty is subject to 48th LRS Operation Instructions and LRS rules. The time constraints associated with generating duties has already been mentioned in the previous section (3.8 preparatory processing). Private duties such as a doctor's appointment are combined with regular duties. Classification constraints are comparatively straightforward. Military personnel can handle both classified legs and non-classified legs. However, civilian drivers like DoD and MoD employees, can be assigned to only non-classified legs. DSS implements separate worksheets for daily and intermittent recurring legs, and this approach leads to the separate consideration of military and civilian jobs.

Generated duties are cornerstones for schedule generation. The next section will provide a through discussion of the process of generating schedule.

3.10 Generating Schedule

	STATUS	DUTY HOURS	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900
Leadbetter	OFF	0530-1800														
Wilmot		0530-1800	Shuttles (39 Pax Bus)					Shuttles (39 Pax Bus)								
Cook	OFF	0700-1930														
Hoare		0700-1930		0800 tractor/trailer run												
Blunt		0700-1930		0900 Zone 3 (1.5 ton Truck)						1300 Zone 3 (1.5 ton Truck)						
Laws		0700-1930		0700 Zone 3 (1.5 ton Truck)				1000 Zone 1&2 (1.5 ton Truck)				1400 Zone 1&2 (1.5 ton Truck)				
P. Milne		0700-1930		0700 Zone 3 (1.5 ton Truck)				1100 Zone 3 (1.5 ton Truck)								
Smith		0700-1930		0900 Transient Aircrew (39 pax bus)												
Rolph		0700-1930		0800 forklift run												
Hammond	LEAVE	0700-1930														
Pentland		0600-1430		Bulk Items (10K forklift)												
Hortenstine		0700-1930		Bulk Items (Tractor/Trailer)												
Black		0700-1930		0800 Non-mil (1 ton truck)						1300 Non-mil (1 ton truck)						
Moore		0700-1930		0730 Zone 7 (1 Ton truck)						1300 Zone 7 (1 Ton truck)						
Davis	Training	0700-1930		0900 Zone 3 (1.5 ton Truck)				1000 Zone 1&2 (1.5 ton truck)				1400 Zone 1&2 (1.5 ton truck)				
Medina	Training	0700-1930		0800 Zone 1&2 (1.5 ton truck)						1200 Zone 1&2 (1 ton truck)						
Battle		0700-1930		0700 Zone 3 (1.5 ton truck)				1100 Zone 3 (1.5 ton truck)								
Braun	Training	0700-1930		0730 Zone 7 (1 Ton truck)						1300 Zone 7 (1 Ton truck)						
Sheets	Training	0700-1930		0800 Zone 4&5 (1.5 ton truck)						1300 Zone 4&5 (1.5 ton truck)						
Sparks		0700-1930														
Barnett		0700-1630														
Adams	LEAVE	0700-1630														
Trissel	Licensing	0700-1630			Test Adams and Barnett on CDCs				Review CDCs with Began							
Hortenstine		0700-1930			AS NEEDED				1000 Zone 1&2				1400 Zone 1&2			
Martinez		0700-1630			493FS (16 Pax Bus)											
Hagens		0700-1630			492FS (16 Pax Bus)											
Bradd		0700-1630			494FS (16 Pax Bus)											
Faulkner	Leave	0700-1630														
Swing shift																
Pauley	Swings	1000-1900						1030 MICAP (Tract/Trailer)				1430 MICAP (Tract/Trailer)				
Galvin	Swings	1500-0001														
Whitmire	Swings	1500-0001														
Harrell	Swings	1500-0001														
Pustka	Swings	1500-0001														
Bullock	Swings	1500-0001														
Beales	Swings	1900-2130														
Mid shift																
Marquez	Mids	1900-0700														
Poff	Mids	1900-0700														
C. Milne	Mids	1900-0730														
Notes																
IF NOT ON A RUN THEN YOU NEED TO BE SERVICING/CLEANING VEHICLES! CHECK IN WITH DISPATCH FOR THE VEHICLES!																
PLEASE LET DISPATCH, TSGT RIETZ, OR SRA TURNER KNOW WHERE YOU ARE IF YOU HAVE TO LEAVE THE SHOP!!																
IF YOU TAKE A VEHICLE OUT OF THE DV BAY PLEASE TOUCH IT UP AND PLACE IT BACK IN THE BAY, LETS STAY AHEAD OF THE GAME!!																

Figure 3-7 Example of 48th LRS's Daily Published Operation Schedule

Figure 3-7 shows an example of an Operation Schedule the 48th LRS currently uses. This is ultimate representation of matching the duties with selected drivers. This section will cover how DSS finds the best combination of duties. Using the baseline legs and initial input parameters in Figure 3-8, DSS found there are 353 eligible duties for shift1 military personnel.

Unit: minutes

<i>Min sit</i>	<i>Max sit</i>	<i>Min workload</i>	<i>Max workload</i>	<i>Shift1</i>		<i>Shift2</i>	
				<i>start</i>	<i>end</i>	<i>start</i>	<i>End</i>
0	120	240	720	07:00	19:00	19:00	07:00

Figure 3-8 Sample parameters

$$\begin{aligned}
 & \min \sum_{j=1}^n c_j x_j \\
 & \text{subject to : } Ax \geq e_m, \\
 & \quad x_j \in \{0,1\} \text{ for } j = 1, \dots, n
 \end{aligned} \tag{5}$$

Equation (5) ensures that each row is covered by at least one column and integrality constraint. Throughout this research, just unicast problem ($c_j = 1$ for all j) is considered. Matrix A is $m \times n$ and all elements are 0 or 1. Figure 3-9 will help to get the concept of SCP. The column D_i ($i=1 \dots 353$) are generated duties, and the rows $\text{Leg } j$ ($j=1 \dots 23$) are baseline legs. For instance, duty 2 covers leg 2, 5 and 22.

	D1	D2	D3	D4	D5	...	D16	D17	D18	D19	D20	...	D353
Leg1	1	0	0	0	0	...	0	0	0	0	0	...	1
Leg2	0	1	0	0	0	...	0	0	0	0	0	...	0
Leg3	0	0	0	0	0	...	0	0	0	0	0	...	0
Leg4	0	0	0	0	0	...	0	1	0	0	0	...	0
Leg5	0	1	0	0	0	...	0	0	0	0	1	...	0
Leg6	0	0	1	0	0	...	0	0	0	0	0	...	0
Leg7	0	0	0	1	0	...	0	0	0	0	0	...	1
Leg8	0	0	0	0	1	...	0	0	1	0	0	...	0
...
Leg20	0	0	0	0	0	...	1	0	0	0	0	...	0
Leg21	0	0	0	0	0	...	0	0	1	0	0	...	0
Leg22	0	1	0	0	0	...	1	0	0	1	0	...	0
Leg23	0	0	0	0	0	...	0	1	1	1	1	...	1

Figure 3-9 SCP & A-Matrix

There are many algorithms and pertinent literatures for solving SCP as the reader can see in the chapter 2. DSS uses the Premium Excel Solver (PES) and SA to get a feasible schedule. Unfortunately, the PES could only handle 200 columns at a time. When the total number of generated duties is less than or equal to 200, no problems arise. However, if it is not the case, then DSS needs tool for solving that kind of problem. For instance, if the DSS results in 353 duties, then the PES will solve the problem with 200 columns and find solution. The solution might be better when considering the extra 153 duties instead of the duties already evaluated in PES.

3.10.1 Pricing Approach

It is assumed that the reader is already familiar with the Excel Solver and Sensitivity Report in Solver. Sensitivity Report shows the original and final values of the objective function and the decision variables, as well as the status of each constraint at the optimal solution.

Pricing approach uses the Microsoft Office's student version of Premium Excel Solver (PES) and that has three different built-in engines to solve the problem. Those three engines are Standard GRG Nonlinear, Standard Simplex LP, and Standard Evolutionary. To use the concept of reduced cost and shadow price, "Standard Simplex LP" engine is implemented. Unfortunately, the PES could only handle 200 variables at a time. When the total number of generated duties is less than or equal to 200, no problems arise. However, if it is not the case, then DSS needs a tool for solving that kind of problem. Advanced solver version (e.g. Premium Solver Platform) could handle up to 2000 linear variables and 8000 constraints. However, the software package is not free.

This kind of financial issue also leads the military users to utilize the built-in engines. The DSS model uses the built-in standard solver engine and modifies to get a solution. For instance, if the DSS results in 353 duties, then the PES will solve the problem with 200 columns and find a solution. The solution might be better when considering the extra 153 duties instead of the duties already evaluated in PES. It sounds like sensitivity analysis. Suppose that the simplex method produced an optimal basis \mathbf{B} with current 200 duties. The point is how to make use of the optimality conditions (primal-dual relationships) in order to find the new optimal solution, if some of the problem data change, without resolving the problem from scratch. In particular, the following variations in the problem could be considered.

- Change in the cost vector \mathbf{c} .
- Change in the right-hand-side vector \mathbf{b} .
- Change in the constraint matrix \mathbf{A} .
- Addition of a new duty.
- Addition of a new leg.

Among those variations, pricing algorithm is associated with “Addition of a new duty”. Suppose that a new duty D_{n+1} with unit cost c_{n+1} and consumption column \mathbf{a}_{n+1} is considered for possible production. Without resolving the problem, it could be easily determined whether producing D_{n+1} is worthwhile. First calculate $z_{n+1} - c_{n+1}$. If $z_{n+1} - c_{n+1} \leq 0$, then $D_{n+1}^* = 0$ and the current solution is optimal. On the other hand, if $z_{n+1} - c_{n+1} > 0$, then D_{n+1} is introduced into the basis and the simplex method continues to find the new optimal solution. The pricing algorithm which is built in DSS will be explained in detail below.

As mentioned before, DSS solves the CSP as a set covering problem. A brief description of the Pricing Approach is given in Figure 3-10.

Step 0 : *Initialization*

Generate 200 duties such that each leg can be covered by at least one leg. These duties consist of initial columns.

Step 1 : *Computation of shadow prices and reduced costs*

Solve PES with the current set of columns. This yield a lower bound for the current set of columns. Then compute the shadow prices for each constraint and reduced costs for each variable (or column).

Step 2 : *Column swapping*

Generate columns with negative reduced cost and swap those columns with positive reduced cost. If no such columns exist, which means the lower bound computed in Step 1 is a lower bound for the overall problem, (or another termination criteria is satisfied), go to Step 3;
Otherwise, return to Step 1.

Step 3 : *Construction of optimal solution*

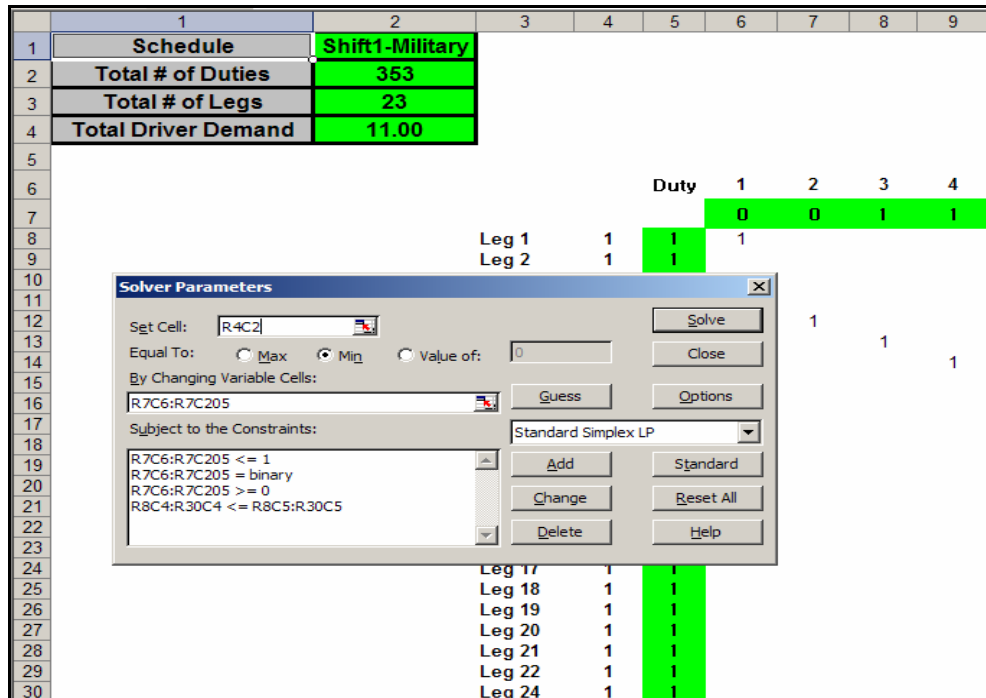
Use all the columns selected in Step 0 and Step 2 to construct an optimal solution.

Figure 3-10 Pricing Algorithm

Suppose that, at some point, K is the set of 200 columns (duties) considered in the master problem. DSS computes the lower bound with respect to these columns via PES and gets the report showing the reduced costs and shadow prices. After calculating the reduced cost of rest columns ($total\ duties \setminus K$), replace the columns of positive reduced cost with columns of negative reduced cost. DSS stops if there are no duties left with negative reduced cost and it implies to obtain a true lower bound. Finally DSS compute an optimal solution by solving a set covering problem in which considered all the columns which has been generated along the way. The final objective value is a real

number, and DSS get the integer objective value via adding integrality and lower bound value into the constraints. To avoid overlapping legs at most, DSS uses different solver setting and resolve the problem. This procedure results in maintaining the same amount of drivers (first objective value) and simultaneously minimizing the number of overlapping legs (second objective value). Figure 3-11 and Figure 3-12 illustrate the solver parameters setting for generating an optimal solution and avoiding overlapped legs, respectively. Avoiding overlapping is a way to transform the set covering problem (SCP) to set partitioning problem (SPP). However, this method does not always guarantee the non-overlapping. Because the optimal solution is generated from SCP not SPP.

By now, pricing algorithm to find optimal solution was detailed. The advantage of DSS model is to use this model as analysis tool. The scheduler may wonder “How many legs could we handle with current status of drivers?” The B-Matrix and priority of each leg do a significant job with this sort of situation. The A-Matrix does not consider the priority of each leg or just assumes they are all “1”, which means should be done for next day. The A-Matrix and B-Matrix are self-defined terms for sub procedure of DSS model. The scheduler could get the optimal drivers amount with the processing of A-Matrix. If the optimal number is less than the current available driver number, then it will be fine. If not, the scheduler would try to minimize the penalty of not satisfying all the requested jobs. Legs with high priority have 10^5 penalty, 10^3 for medium priority legs, and 10 for the low priority legs. The processing of B-Matrix results in how many legs with each priority could not be satisfied and what the legs are. Simultaneously, the result schedule has the evenly distributed work load among drivers.



3.10.2 Heuristic (Simulated Annealing)

The meta heuristic Simulated Annealing combined with Set Covering Problem (SCP) is also implemented here to find the minimum duty number to cover all legs. As mentioned in chapter 2, SA has four elements to consider. They are representations of possible solutions, generator of random changes in solutions, means of evaluating the problem functions, and annealing schedule.

3.10.2.1 Representations of possible solutions

‘Possible solutions’ is not an ultimate solution but a solution for PES. With this solution the Excel runs the premium solver and produces an ultimate solution for DSS. The SA starts its process with random initial solution. The better the initial solution is, the less processing time takes. Two points are intuitive at selecting initial solution: 1) all only-one-leg duties should be included in the 200 duties for PES. An only-one-leg duty is a duty which has no room for other legs. Therefore, there is no two-leg duty combining the only-one-leg duty with other leg. 2) Five-leg duties are more efficient than one or two-leg duties. There might be an arguing point here, however in general it does make sense when considering initial solution.

‘On duty array’ (Figure 3-13) is a set of 200 duties which is chosen for the PES. Considering the two points mentioned above, DSS generates an initial solution, and checks whether the chosen duties cover all legs. If the ‘on duty array’ does not satisfy feasibility conditions, then random duties are chosen from the ‘off duty array’ switched with duties from the ‘on duty array’ and then checked for feasibility. This process continues until a feasible solution for PES is found.

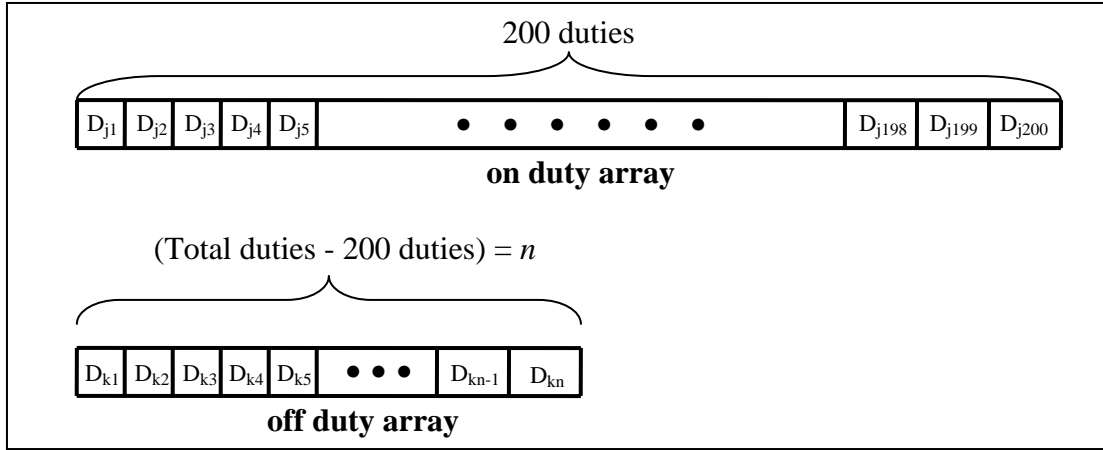


Figure 3-13 Representation of possible solution

3.10.2.2 Generator of random changes in solutions

After evaluating the initial random solution, the SA generates random changes in solutions. This change is also done by picking random duties from an updated ‘off duty array’. As the heuristic process goes on, two arrays are updated and store new information iteration by iteration. 10 on duties and 10 off duties are chosen for swapping and after checking the feasibility of 200 duties, the new ‘on duty array’ and ‘off duty array’ is produced. 10 of 200 duties correspond to 5% swap, and the choice of this percentage is arbitrary. Any percentage could be possible.

3.10.2.3 Means of evaluating the problem functions

The objective function value of this model is to minimize the number of duties covering all legs. To evaluate the solutions, DSS checks the objective value and keep track of the value. When the current solution has an objective value less than or equal to the previous solution’s objective value, DSS will update the ‘on duty array’ with the current solution. However, when the current objective value is greater than the previous

objective value and the randomly generated probability of acceptance is greater than the Metropolis distribution, the current solution returns to the previous solution and the process is continued. This stochastic process reduces the probability to accept the non improving move solution. Alternative approach is to minimize the penalty function value. When there is driver shortage compared to the demand, then the penalty value has positive value ($=\text{demand driver number} - \text{current driver number}$). The demand driver number is the current solution of PES and might not be the feasible one. While the penalty value is positive, the solution is infeasible and SA will search toward the feasible solution area. When the SA can not get a feasible solution with current driver level, then DSS produces an alert message and asks to reduce the number of legs depending on the priority level. Then DSS will continue to search for a feasible solution.

3.10.2.4 Annealing schedule

Annealing is the process of heating metal or glass and allows it to cool slowly, in order to make it harder. For SA, DSS uses a starting temperature of 50 degrees. It then reduces the temperature by a factor of 0.05 with an end temperature of 10 degrees. In one temperature level, SA will generate 100 total replications, compare the objective function value and update the solutions for next iteration. As the process arrives at 20 degrees, the temperature is then reduced by a factor of 0.01. This change will make the process search the solution area more thoroughly.

3.11 Summary

This chapter presented the methodology for solving the squadron-scheduling problem. The pricing algorithm provides lower bound for the required number of drivers (first objective value) and also builds least overlapped scheduling plan (second objective value). The scheduling process in DSS can be summarized by the 5 steps. 1) The scheduler starts the DSS by building appropriate parameter. In reality, the scheduling parameter is fixed during some specific time period. The scheduler could use this model as an analysis tool for future working environment. 2) Receive the daily recurring jobs and intermittent recurring jobs. This step could be done simultaneously with step 3) Prioritize the jobs / check the availability of drivers and their qualification. Daily recurring jobs have priority 1, which means those jobs should be done. However, the intermittent jobs' priority is dependent on the scheduler. This model provides the tool for checking the feasibility whether the VOE could handle the whole requirements from every customer under current drivers status. 4) Generate eligible duties. Eligible duties are those which satisfy the parameter set-up conditions (e.g., shift time, meal consideration, sit time, work load, etc). 5) Generate a schedule. This is the final step for DSS. Next chapter details how the methodology was tested and the results of this testing.

Chapter 4. Analysis and Results

4.1 Chapter Overview

This chapter describes the analysis of the schedules generated to meet the current scheduling environment. The development of the Daily Squadron Scheduler required testing to ensure that the model performed quickly and could solve the appropriate problems. This chapter is broken up into two sections. The first section analyzes various scheduling scheme and their results with current daily recurring jobs. The second section sets up many notional delivery scheduling composed with daily recurring jobs plus various intermittent jobs, and analyze the results.

4.2 Physical Structures and the Performance of the Software

The software design can be measured by looking at the interface environment and the flexibility of the software in the scheduling generation process. The software interface environment is straightforward and user friendly. DSS is composed of eight worksheets. “Explanation” is the main menu provides a list of choices for the user to enter parameter setup, copy the daily recurring jobs, input legs data into formatted spreadsheet, execute the model or exit the program completely. Figure 4-1 shows the start up menu. “LRS DATA” is baseline spreadsheet containing daily recurring jobs both military and civilian. Whenever there is a change with daily recurring jobs, the scheduler could update manually the data in the spreadsheet. This information will be

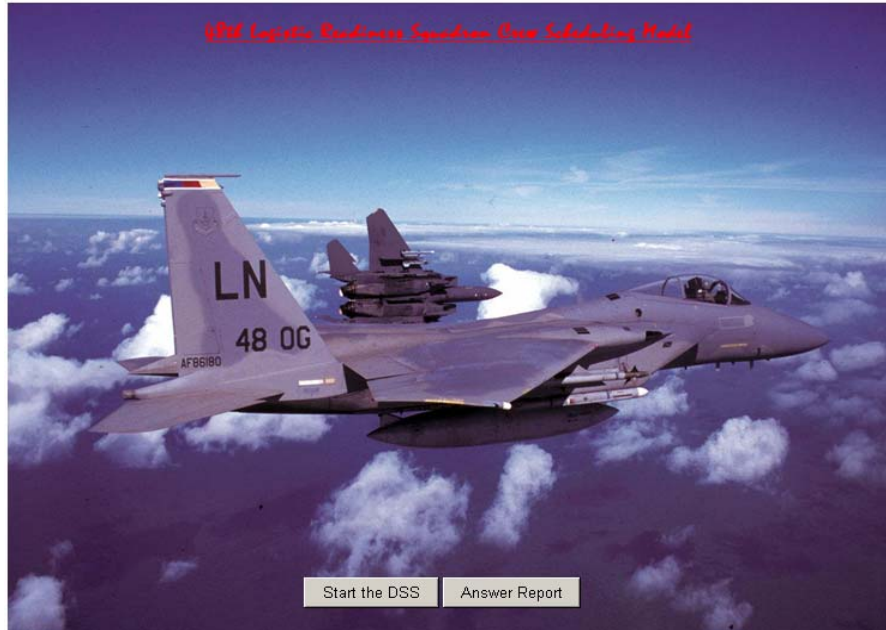


Figure 4-1 Start Up Menu

automatically copied at “Customer for Military Personnel” or “Customer for Civilian Drivers” when *create new customers* button in the User Option form is executed.

“Customer for Military Personnel” and “Customer for Civilian Drivers” are spreadsheet for containing the leg data for military and civilian respectively. The Excel spreadsheet allows manual overrides of most functions to provide the squadron scheduler with maximum flexibility. The scheduler input intermittent recurring jobs into the spreadsheet either using main menu or writing directly on the spreadsheet. “A-Matrix” is used for calculating the optimal number of required drivers and “B-Matrix” is used for figuring out the possible legs with current driver number. Throughout the processing, the scheduler could trace the results of objective function value as Solver updates the value at the specific cell in “A-Matrix” or “B-Matrix”. “Total Schedule” and “Answer Report” are the results of schedule and its statistics for the schedule, respectively.

4.3 Parameters Analysis

Note that both meta heuristic SA algorithm and pricing algorithm are introduced in chapter 3. As some sample problems are implemented under the SA algorithm, several significant facts were found. First, the heuristic generates the solution based on randomization. At one temperature, the algorithm explores the solution space, picks a specific solution randomly and selects the solution according to the improvement condition or probability. After a fixed number of iterations, it will be cooled and the process will be continued until the temperature reaches the preset degree. This kind of approach is seriously time-consuming as the problem size increases dramatically. Second, it can be shown that, for any given finite problem, the probability that the simulated annealing algorithm terminates with the global optimal solution approaches 1 as the annealing schedule is extended. This theoretical result is, however, not particularly helpful, since the annealing time required to ensure a significant probability of success will usually exceed the time required for a complete search of the solution space. Third, theoretically, the SA will converge to the optimal solution given an appropriate cooling schedule. Without the appropriate cooling schedule, the optimality could not be guaranteed. Thus, the solution of SA is not good as the one which is resulted from pricing algorithm. Therefore, only pricing algorithm results will be analyzed throughout this chapter.

Table 4-1 Factors and Levels

Factor	Level
Shift	4 (1 shift, 2 shifts, 3 shifts, 4 shifts)
Minsit	4 (0, 30, 60, 90)
Maxsit	4 (30,60,90,120)
Mealbreak	7 (1, 2, 3, 12, 23, 123, 0) 1 : shift1_meal, 2 : shift2_meal, 3 : shift3_meal, 0 : no meal consideration
Maxworkload	5 (510,540,600,660,720)

To show DSS model's capability, full factorial experiment was executed. Table 4-1 shows the factors and levels for each factor. Shift factor has four levels of one shift (7:00–7:00), two shifts (7:00–19:00 / 19:00–7:00), three shifts (7:00–16:00/16:00–0:00/0:00–7:00), and four shifts (7:00–13:00/13:00–19:00/19:00–1:00/1:00–7:00). Minsit is minimum time for resting between two consecutive legs, and Maxsit is maximum allowable time for resting between two consecutive legs. Note that there is no case which minsit is greater than maxsit. Therefore, there are 13 (4+4+3+2) possible combinations for minsit and maxsit. Meal break has 6 possible levels, and each meal break time is fixed here as follows: shift1_meal (5:00–7:00), shift2_meal (11:30–13:30), and shift3_meal (17:30–19:30). With four shifts scheme (each shift has 6 hours workload) there is no reason to allow drivers to take an hour meal break. That's why the experiment excludes the meal consideration for the four shifts. As explained in chapter 3, every leg which is associated with those meal break time has artificial start or finish time. Finally, five levels are considered for maxworkload. The experiment has total points of 1235 for each military and civilian (3 shifts×13×6×5 + 1 shift×13×1×5). After running all points, one interesting result was found. For the military schedule, equal amount of minsit and maxsit (30 and 90) resulted in the maximum number of drivers regardless of

other parameter settings. Those combinations which include equal minsit and maxsit (30 and 90) was deleted from the data for analysis purpose. The revised experiment has total points of 1045 for military schedule. For the civilian schedule, there are no specific schemes for maximum number of drivers, therefore all experiment points of 1235 is analyzed. Next sub section shows the results of experiments with already explained several parameter setups.

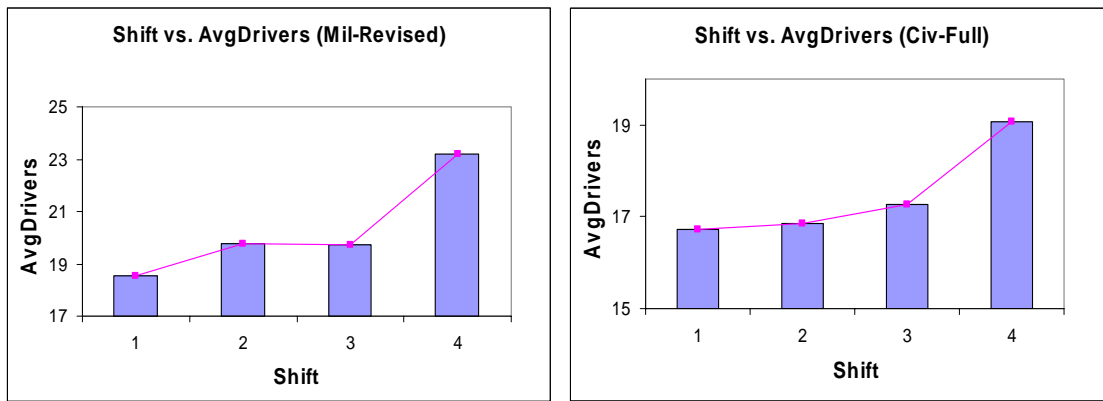


Figure 4-2 Shift vs. AvgDrivers

Shift vs. AvgDrivers shows the relationship between various number of shifts and average number of drivers. One shift scheme has the smallest average number among other shifts number, and this results from the flexibility of one shift schedule. Note that a leg should be categorized into a shift by some time constraints and those legs in same shift could be combined to build duties. Therefore, as the shift number grows the flexibility to the legs decreases. Both military and civilian results show common trend of the more shift, the more drivers.

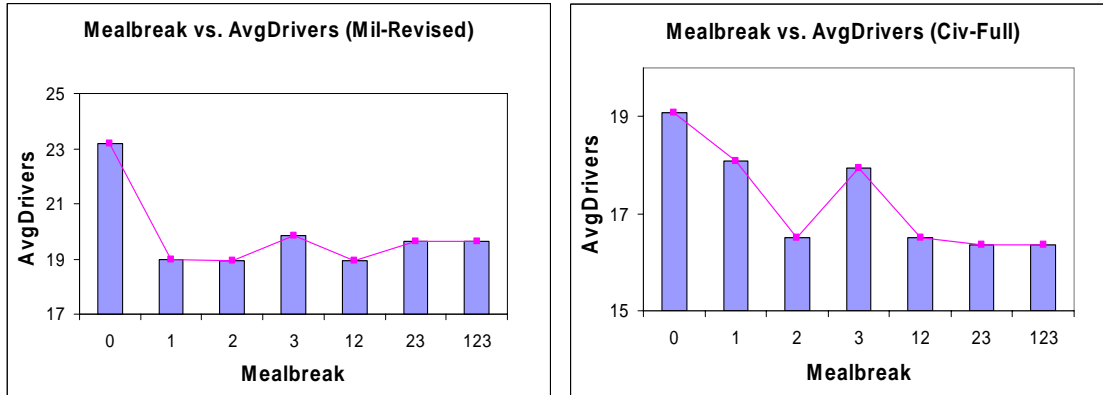


Figure 4-3 Mealbreak vs. AvgDrivers

Mealbreak vs. AvgDrivers shows the relationship between various meal break consideration and average number of drivers. Mealbreak “0” means there is no consideration for the schedule and this case is applied to the 4 shifts scheme. This is why mealbreak “0” has the most value among other meal values. Except mealbreak “0”, the results show no big difference between rest 6 meal considerations. Commonly, mealbreak parameter does not have any effect on both military and civilian schedule.

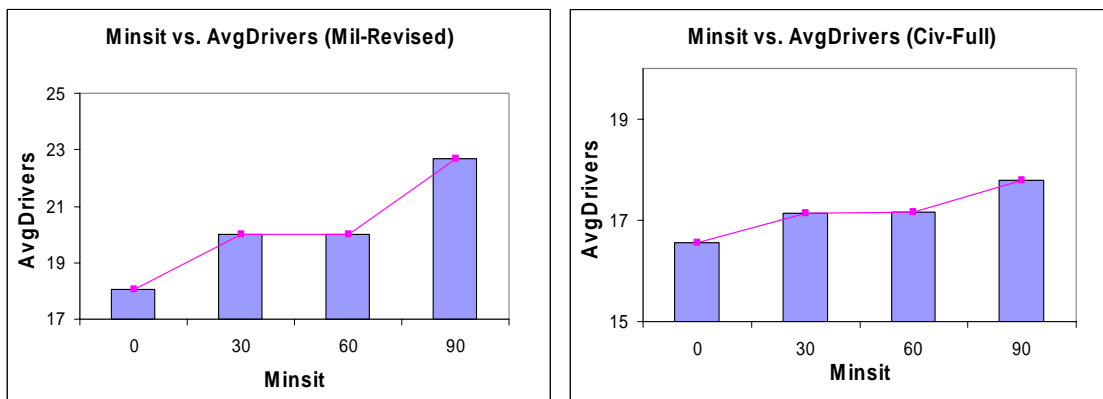


Figure 4-4 Minsit vs. AvgDrivers

Minsit vs. AvgDrivers graph shows the trend of “more minsit, more drivers”.

This result is consistent with intuition that as the minimum sitting time is growing, more drivers will be needed for accomplishing the jobs.

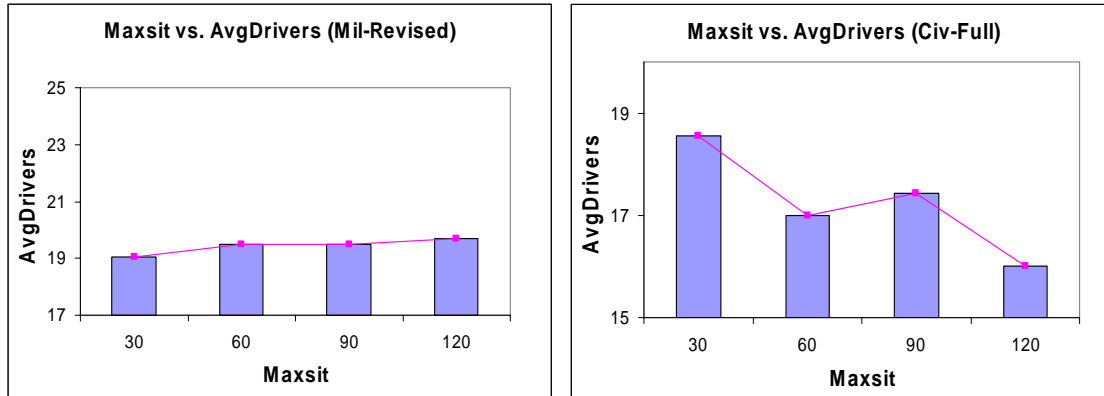


Figure 4-5 Maxsit vs. AvgDrivers

Maxsit vs. AvgDrivers show the relationship between maxsit time and average number of drivers. Maxsit time has different attribute with minsit time, while minsit is an obligation or a strict constraint, maxsit is a sort of upper bound like maximum allowable resting time. Intuitively, the tight maxsit will result in more drivers, and civilian result follows the intuition. However, the military schemes don't show that kind of trend.

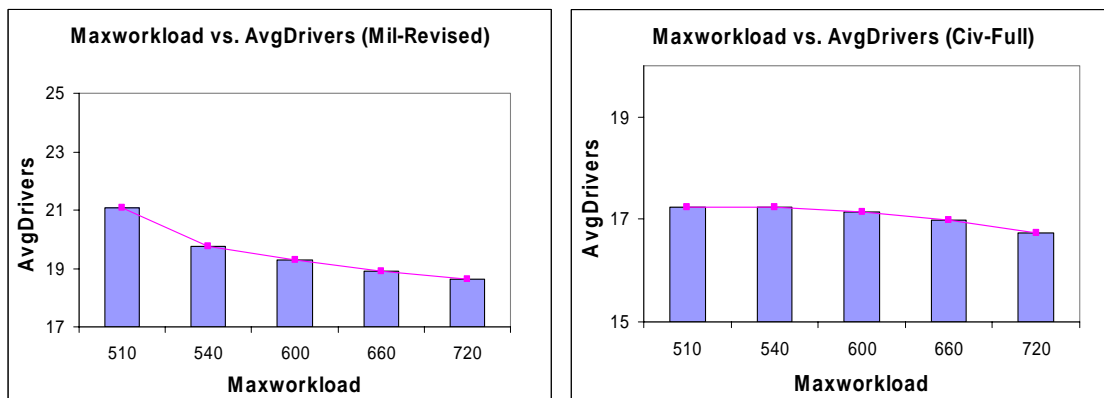


Figure 4-6 Maxworkload vs. AvgDrivers

Finally, Figure 4-6 demonstrates how the max workload influences the average number of drivers. As the maximum workload increases, the LRS could save many drivers. There is linear relationship on those two variables. In reality, max workload of 720 minutes is hard to imagine.

Note that shift number, minimum sit time and maximum workload parameters have more impact on the required number of drivers than the other parameters like meal consideration and maximum sit time. Next section will explain possible “the best” combination of parameters, and this implication will provide an idea to the LRS scheduler.

4.4 Scheduling Scheme with Daily Recurring Jobs

Figure A-1 and A-2 on Appendix A are current LRS’s schedule for military and civilian drivers. They are a specific day’s responsibilities for daily recurring jobs and depend on days. Table 4-2 demonstrates the brief analysis of current LRS’s schedule. AvgWL is the value for average work load of all required drivers, and MinWL(or MaxWL) are not values as parameter but results value for minimum(or maximum) work load among respective drivers.

Table 4-2 Current LRS Schedule Summary

	Drivers	AvgWL	MinWL	MaxWL
Military	17	6.73hr (445min)	3hr (180min)	12hr (720min)
Civilian	15	6.96hr (418min)	2hr (120min)	12hr (720min)

4.4.1 Military Schedule Comparison

Table 4-3 DSS Results Summary (Military)

Drivers	Total	Shift				Max workload (Parameter)					AvgWL (Result)			
		1	2	3	4	510	540	600	660	720	~325	~375	~410	~450
16	68	39	29				2	9	12	45				68
17	130	59	25	46		12	26	34	41	17			122	8
18	145	59	53	33		6	20	36	41	42			145	
19	227	86	44	97		19	61	43	57	47		218	9	
20	151	49	60	42		37	34	34	23	23		151		
21	162	25	47	70	20	56	40	30	18	18	102	60		
22	58	13	33	12		36	7	7	4	4	58			
23	31		21	10		20	2	5	2	2	31			
24	59		9	20	30	16	13	10	10	10	59			
25	6		6			3	3				6			
26	3		3			3					3			
27	5				5	1	1	1	1	1	5			
31	190	60	60	60	10	38	38	38	38	38	190			

Table 4-3 summarizes the results of the DSS model for military. Drivers column is a calculated required drivers number associated with three considerations (shift, max workload, and AvgWL). Total column is the total number of schemes which has the attributes of three considerations. For instance, there are 68 schemes of producing 16 drivers and those AvgWL are within the range of 411~450 minutes. The DSS model resulted in 68 schemes with 16 drivers and 130 schemes with 17 drivers. Two observations could be drawn from the results. First, the more drivers, the less max workload. Second, the AvgWL decreased as the number of driver increases. These two insights are surely self-explanatory. Considering reasonable schemes, which means max workload is less than or equal to 540, there are 2 schemes with 16 drivers and 38 schemes with 17 drivers. Intuitively, schemes of 16 drivers and 540 maximum work load in Table 4-3 look better than the current schedule in Table 4-2. To ensure that the model

performed quickly and could produce more man power saving schedule, thorough investigation into the found schemes should be done.

Those two schemes of 16 drivers with 540 max work loads are more completely described in Figure 4-7. The difference between those two schemes is only the meal consideration (1 and 12). The tremendous merit of these schemes is to save one driver. Also, the DSS model's AvgWL (423.75min) is less than the current schedule's AvgWL (445min). Figure 4-9 and Figure 4-8 illustrate the DSS model's output and current LRS scheduler's output. Apparently, DSS model produced a good schedule with less average work load time and less drivers.

Parameters					Results			
Shift	Minsit	Maxsit	Mealbreak	Maxwork	Drivers	AvgWL	MinWL	MaxWL
1	0	120	2	540	16	423.75	120	540

Workload	120	300	360	420	480	540
No. Drivers	1	2	2	1	8	2

Parameters					Results			
Shift	Minsit	Maxsit	Mealbreak	Maxwork	Drivers	AvgWL	MinWL	MaxWL
1	0	120	12	540	16	423.75	120	540

Workload	120	300	360	420	480	540
No. Drivers	1	2	2	1	8	2

Figure 4-7 Combination of Parameters for Military Schedule (1) & (2)

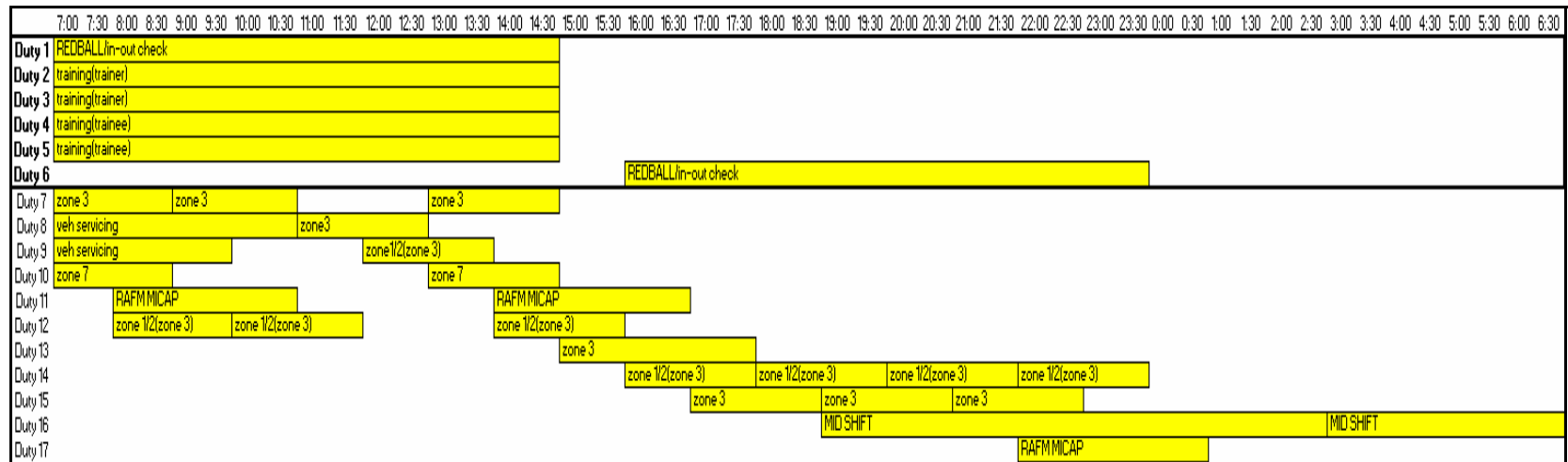


Figure 4-8 LRS Current Military Schedule

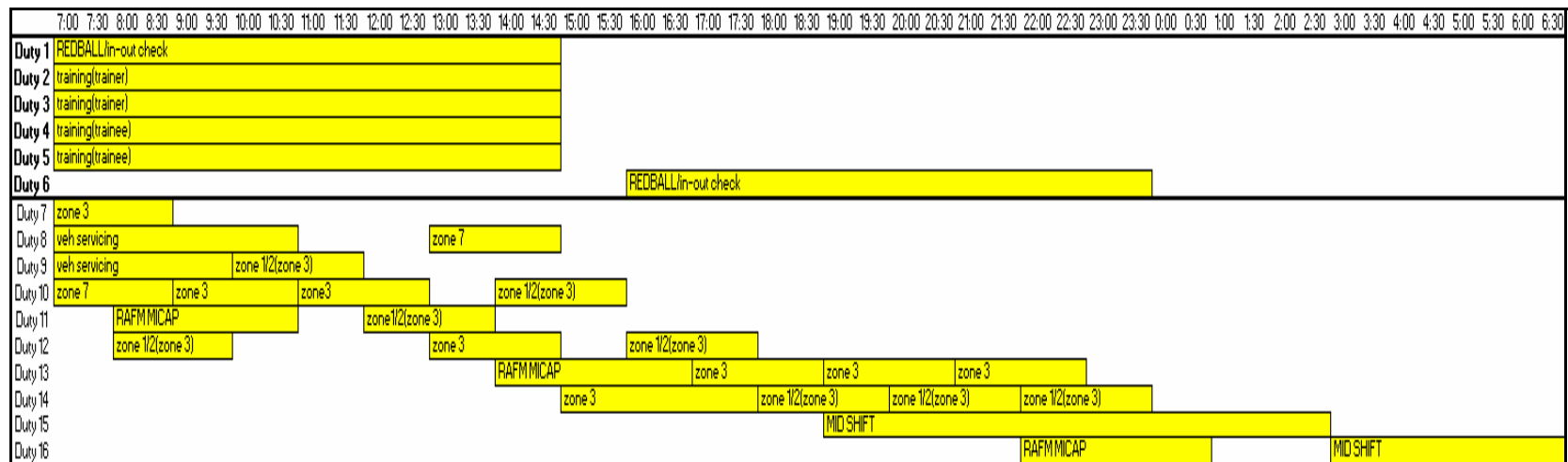


Figure 4-9 DSS Military Schedule (1)

4.4.2 Civilian Schedule Comparison

Table 4-4 DSS Results Summary (Civilian)

Drivers	Total	Shift				Max workload (Parameter)					AvgWL (Result)			
		1	2	3	4	510	540	600	660	720	~305	~345	~390	~450
14	28	14	14							28				28
15	191	91	56	44		16	16	38	70	51			191	
16	391	125	150	116		106	106	84	52	43			391	
17	120	20	30	70		20	20	20	20	40		120		
18	180	60	60	40	20	38	38	38	43	23		180		
19	214	54	50	90	20	44	44	44	39	43	214			
20	111	26	30	30	25	23	23	23	23	19	111			

Table 4-4 summarizes the results of the DSS model for civilian. The model resulted in 28 schemes with 14 drivers and 191 schemes with 15 drivers, etc. The same insights could be drawn from the observations as military schedule. Considering reasonable schemes, which means max workload is less than or equal to 540, there are 32 schemes with 15 drivers and no schemes were found with 14 drivers. Every 14 driver scheme has 720 minutes of max work load. In the view of saving manpower, DSS schedule is better than the current LRS schedule. In the view of minimizing max work load, DSS products show 16 schemes have 510 minutes of max work load. However, current schedule has 720 minutes of max workload. It proved that DSS model produced more time and man power saving schedules than current schedule. Time saving implies not only the schedule producing time, but also the AvgWL of DSS model (386) is less than the current LRS's schedule (418 minutes, Table 4-2). To ensure that the model performed quickly and could produce more than man power saving schedule, thorough investigation into the found schemes should be done.

The best scheme of 14 drivers with 720 max workload and the best scheme of 15 drivers with 510 max workload are more completely described in Figure 4-10.

Parameters					Results			
Shift	Minsit	Maxsit	Mealbreak	Maxwork	Drivers	AvgWL	MinWL	MaxWL
2	0	120	123	720	14	413.57	120	720

Workload	120	180	360	480	510	540	720
No. Drivers	1	2	3	3	3	1	1

Parameters					Results			
Shift	Minsit	Maxsit	Mealbreak	Maxwork	Drivers	AvgWL	MinWL	MaxWL
1	0	120	123	510	15	386.00	180	510

Workload	180	240	300	360	480	510
No. Drivers	2	1	1	4	4	3

Figure 4-10 Combination of Parameters for Civilian Schedule (1) & (2)

Civilian schedule (1) explains that there is only one 720 work load duty and 540 work load duty. Considering the current schedule in Appendix A, there is no difference in AvgWL with DSS schedule. However, DSS schedule save one driver with same amount of work load. It is absolutely better schedule than current schedule in the situation of man power shortage. Civilian schedule (2) shows the distinct advantage of DSS output. Note that this schedule guarantees every meal consideration, 30 minutes less AvgWL than current schedule, and there is no more work load than 510 minutes. Remind that the current schedule forced a driver doing a burden of 12 hours work load. Figure 4-11 and Figure 4-12 illustrate the DSS model's output and current LRS scheduler's output. The first eight duties surrounded by bold line are exactly same between two schedules, however there is a little difference at the rest duties. Duty15 in current schedule is one leg duty while the shuttle (39pax) leg is combined into duty9 in DSS schedule.

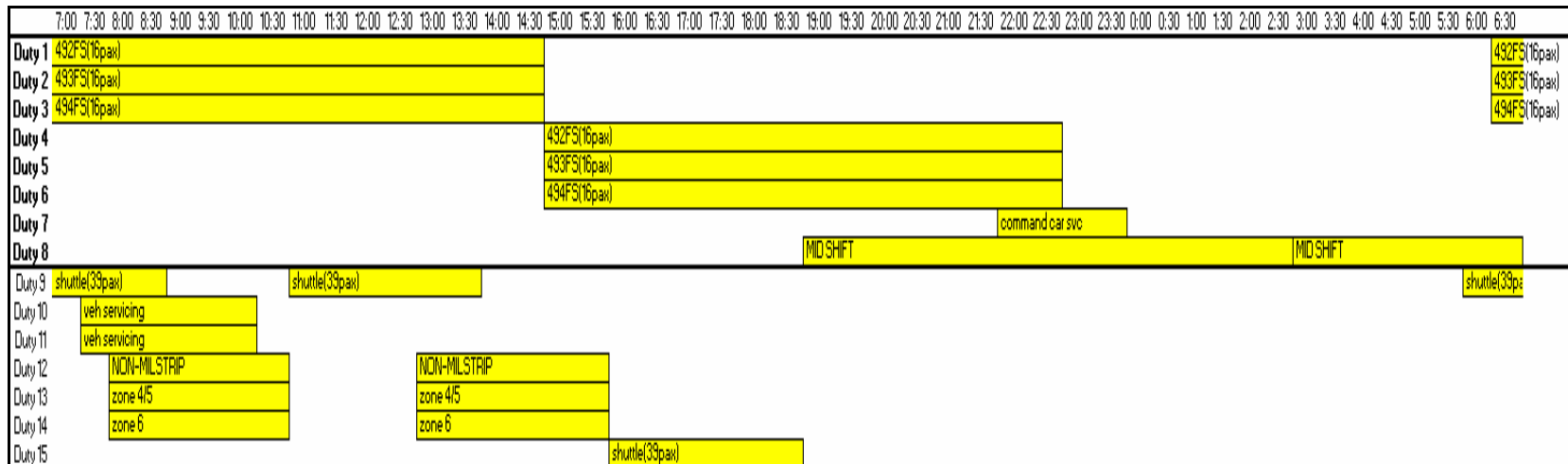


Figure 4-11 LRS Current Civilian Schedule

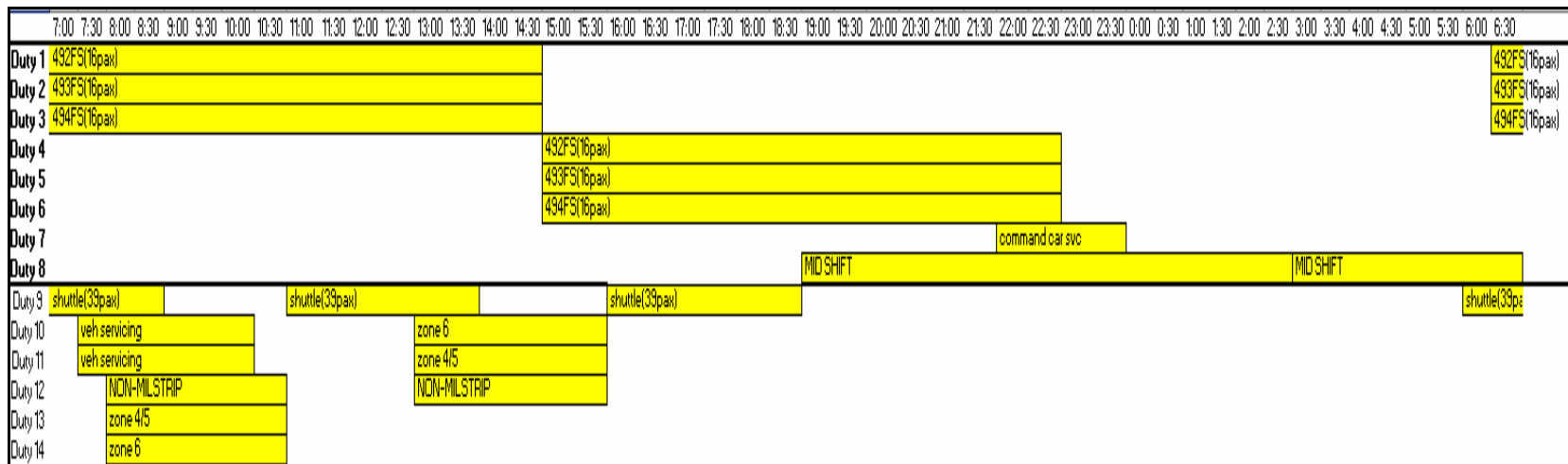


Figure 4-12 DSS Civilian Schedule (1)

4.5 Notional Schedule

At the previous section, daily recurring schedule was produced and compared with current schedule. This section does notional schedules which are created to test the capability of DSS model. The model's performance can be measured with the produced number of drivers and the quality of schedule (e.g. overlapping duties). DSS produces military and civilian schedules separately. The military schedule analysis could be expanded to the civilian schedule analysis. Therefore, just military schedule was considered in this section. Three duplicates of military daily recurring legs were used to set up the notional schedule environment. These notional schedule was run on a 730MHz laptop computer with 256MB RAM. Based on the more modernized computer, the algorithm would be expected to generate schedules as fast as, or faster than the test machine.

Table 4-5 Notional Run Set Up & Results

Shift	Minsit	Maxsit	Mealbreak	Minwork	Maxwork
1	0	120	2	300	540
Leg number		31	62	93	124
Drivers	Calculated	16	32	49	65
	Optimal	16	32	48	64
	Gap	0 (0%)	0 (0%)	1 (2%)	1 (1.5%)
Computation time		32.01	63.05	191.22	691.80
Total duties		255	2,082	7,815	20,748

The notional scheduling environment was used as scheduling input to generate schedules for the analysis. Table 4-5 explains the setup for notional experiment. Note that this scheme with 31 daily recurring jobs produced 16 drivers at military schedule,

and this is the optimal solution. This algorithm implements the pricing method, and the fact that there are no negative reduced cost duties at last iteration guarantees optimality. The graphs in next section show the results of DSS notional run and their schedules depend on leg numbers, respectively.

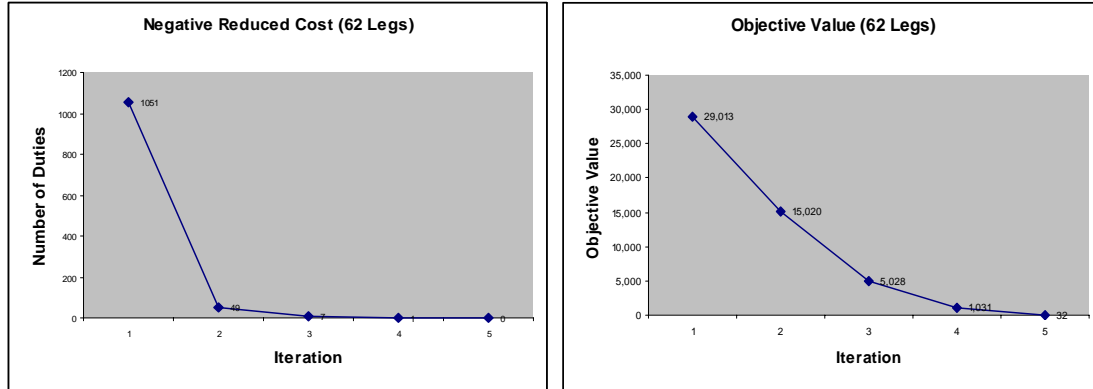


Figure 4-13 DSS Notional Run Results (62 Legs)

First duplicate (62 legs) has only five iteration of Solver, and at the last iteration it reached at the optimal solution with none negative reduced cost (Figure 4-13). The schedule demonstrates there are 4 over lapped legs. Note that this is SCP and the overlapped legs could be converted to other legs or just deleted from consideration.

Second duplicate (93 legs) has 18 iteration of Solver, and at the last iteration it reached at the optimal solution. The LP solution of this duplicate has 48 drivers, but the IP solution (Figure 4-17) shows they required one more driver. This is resulted from the stopping criteria of pricing algorithm. Solver search through the solution area with negative reduced cost and stopped when there is no improving duty. There are so many optimal LP solutions, and the algorithm picked one of them. Apparently, the LP solution

does not guarantee the IP optimal solution. Reader could imagine the lower wide plateau of optimal solution area as the problem size is growing.

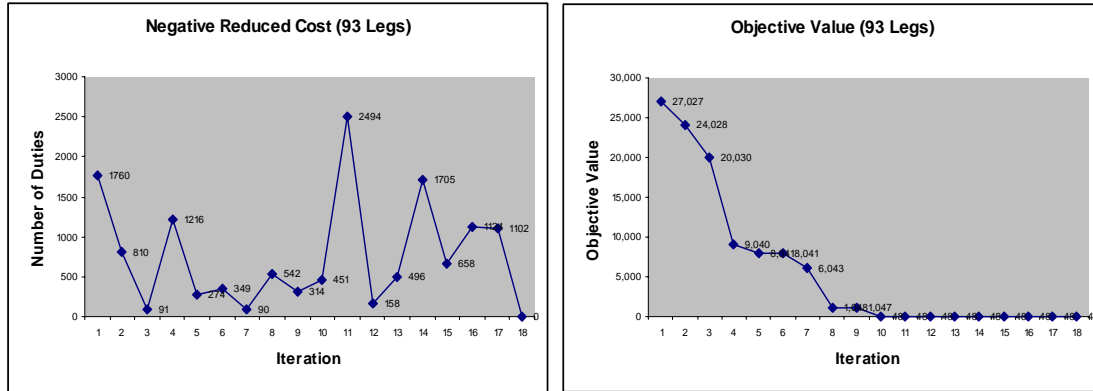


Figure 4-14 DSS Notional Run Results (93 Legs)

Third duplicate (124 legs) has the same phenomenon with the second duplicate one. Note also that there are more overlapped legs as the problem size is increased. Based on the current daily recurring jobs of LRS, 124 legs are unrealistic number. Despite of that, DSS model solved and did a schedule with reasonable calculation time. Figure 4-15 shows the results of 124 legs. Left two graphs are pictures of at a glance, and right two graphs are magnified ones at the iteration range of 3 to 47. At early iteration (1 to 3), steep decrease in number of negative reduced cost duties and objective value could be observed. Trend line (5per) explains the trend of the graph at every 5 iterations. Note that the trend line (5 per) of “Negative Reduced Cost” is bouncing up and down, however the peak point of the line is decreasing to reach the optimal point of zero. The trend line (5 per) of “Objective Value” is less steep than first three iterations, but its value also gradually decrease to the optimal point of 64 finally.

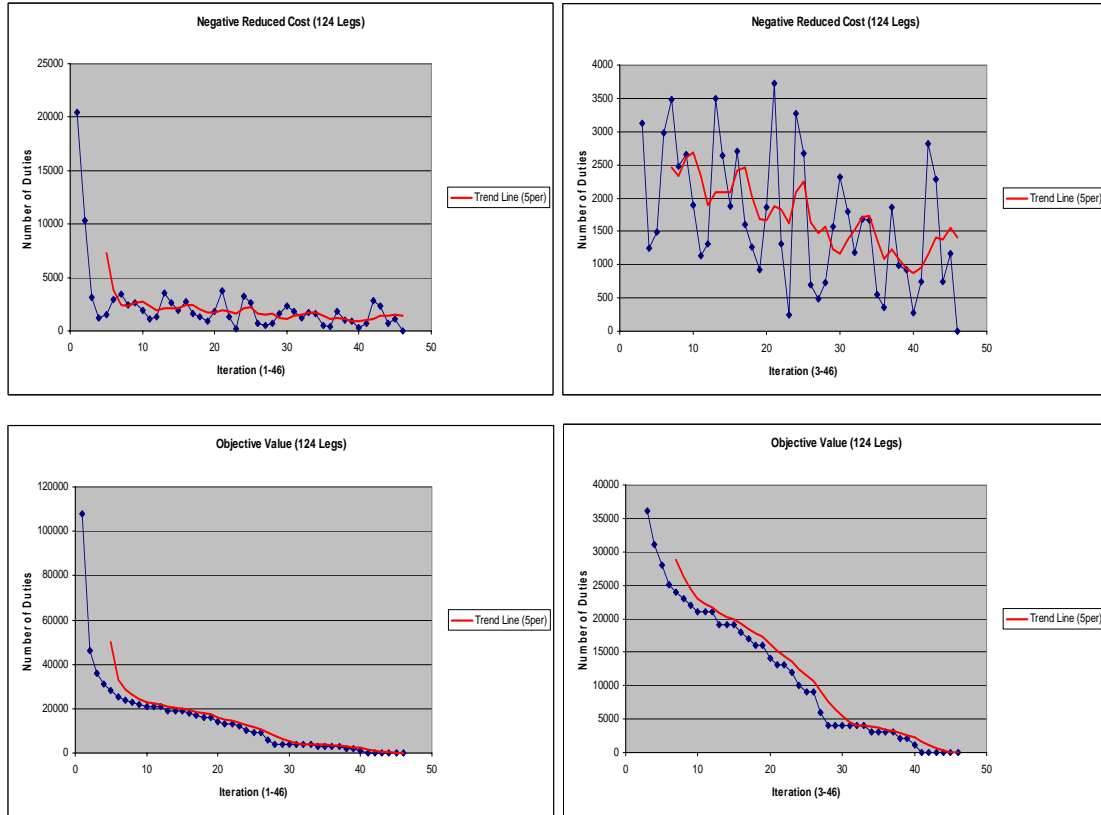


Figure 4-15 DSS Notional Run Results (124 Legs)

Next three graphs are generated schedules for 62, 93, 124 legs, respectively. 62 legs schedule required 32 drivers and there are 4 legs which are overlapped. 93 legs schedule required 49 drivers and there are 8 legs which are overlapped. 124 legs schedule required 65 drivers and there are 9 legs which are overlapped. These overlapped legs could be deleted and changed with new legs. Note that this pricing algorithm is based on not SPP but SCP. That's why overlapped legs were generated.

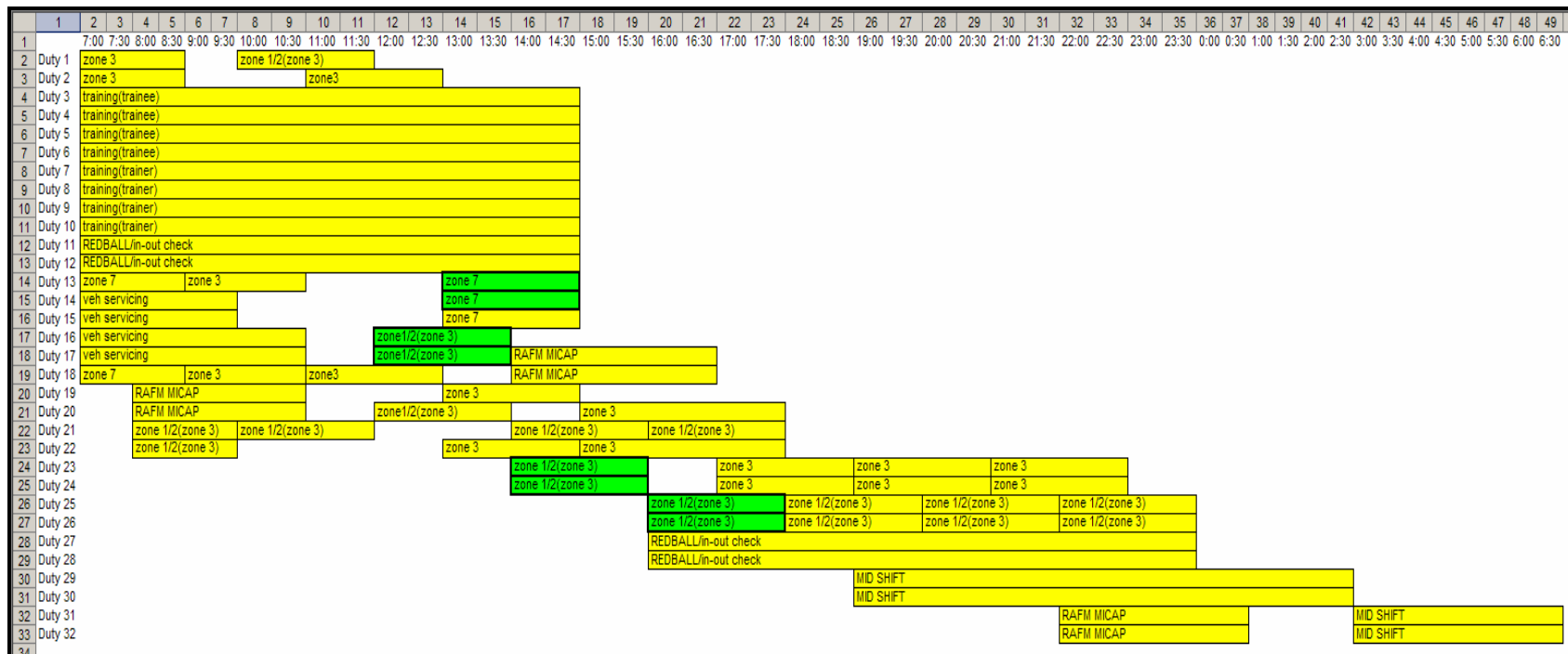


Figure 4-16 DSS Notional Run (62 Legs)

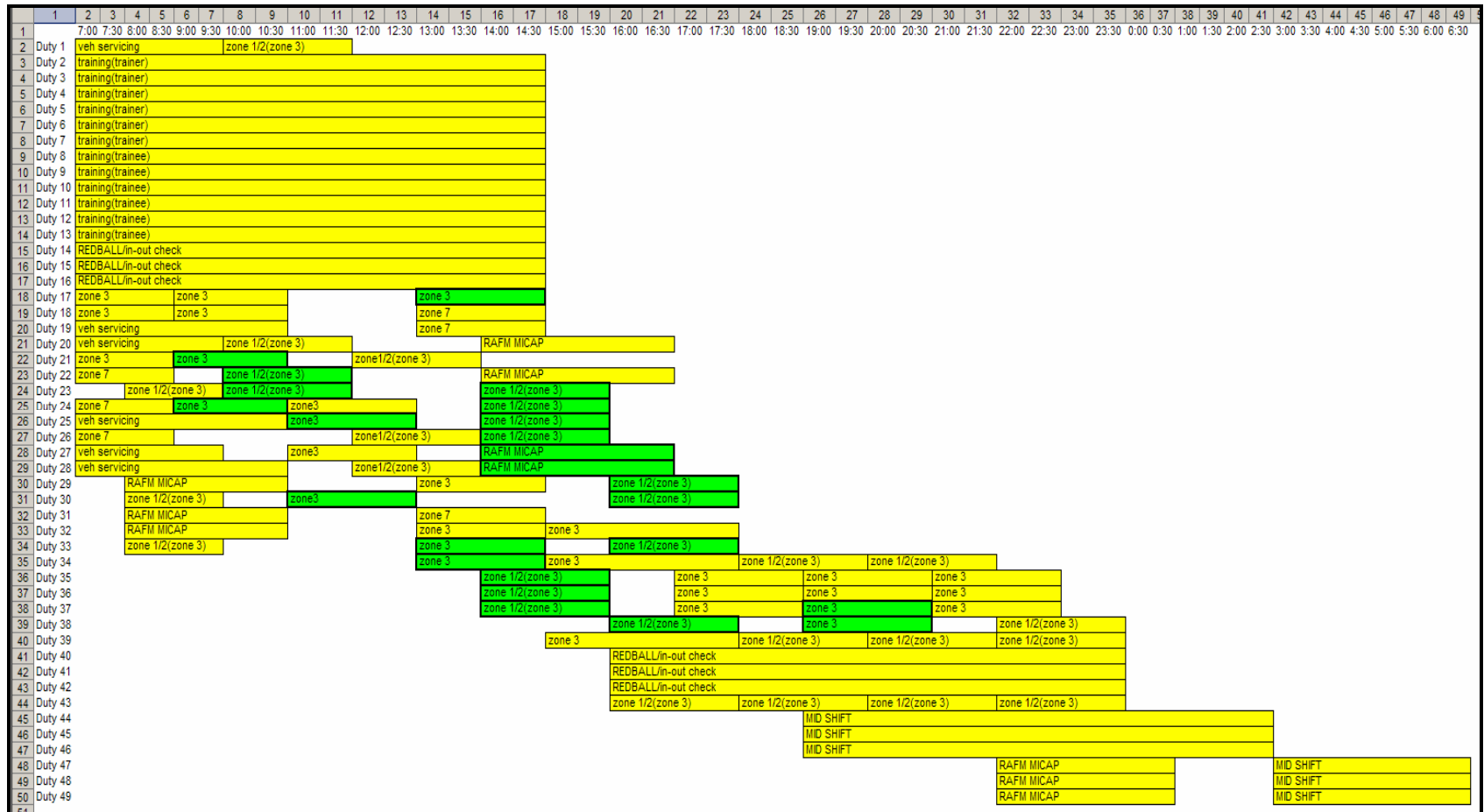


Figure 4-17 DSS Notional Run (93 Legs)

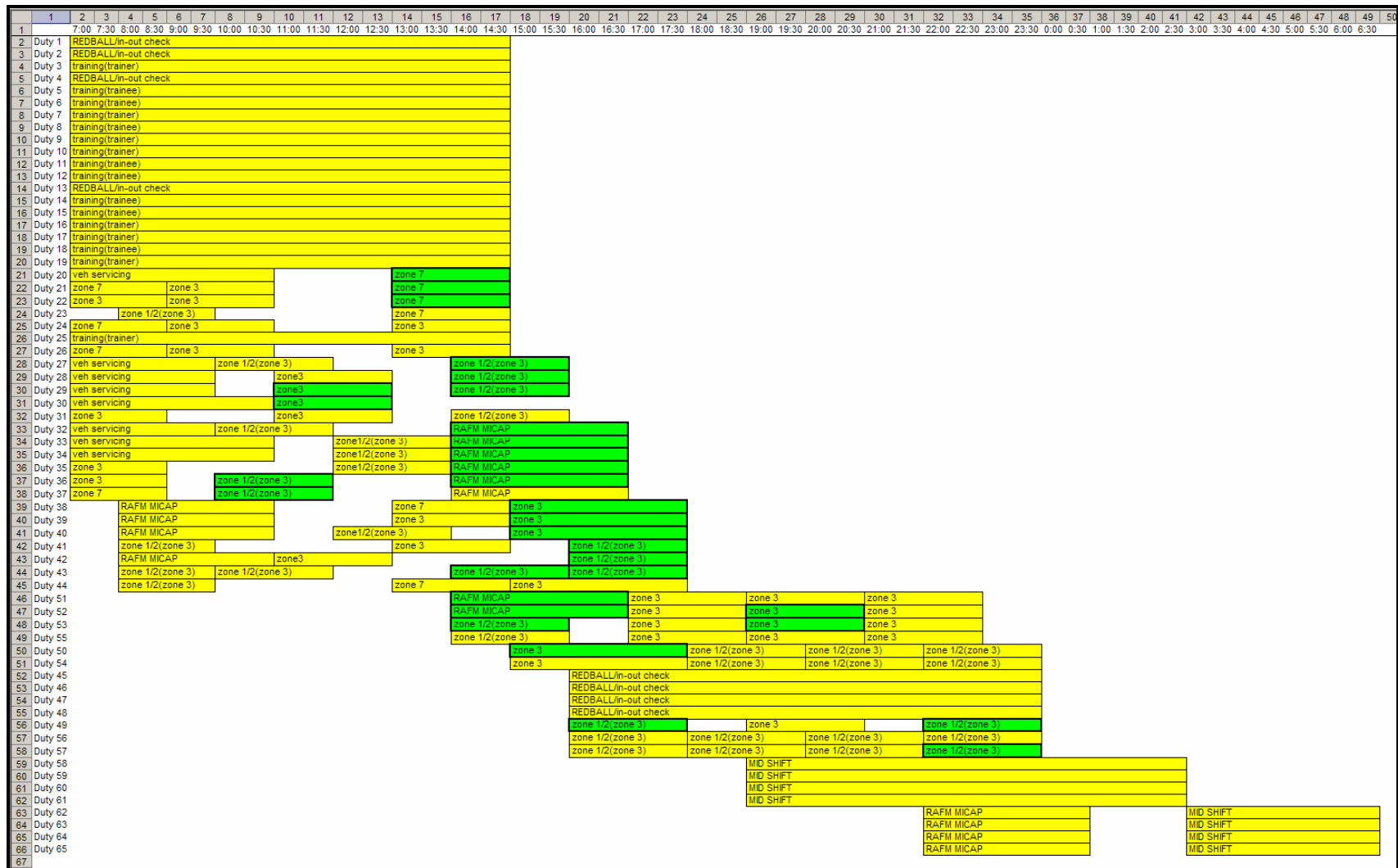


Figure 4-18 DSS Notional Run (124 Legs)

4.6 Conclusion

DSS model provides the scheduler with both a scheduling tool and analyzing tool. Throughout the parameter analysis it was found that shift number, minimum sit time and maximum workload parameters have more impact on the required number of drivers than the other parameters like meal consideration and maximum sit time.

Pricing algorithm was examined with the daily recurring jobs and notional jobs environment. It was found that DSS could handle large scale problems beyond current LRS schedule size. The LP solution of the large problems are equal to the optimal solution, however it requires one more driver with some IP solution.

Not only the optimal solution, but also the solution which minimize the penalty could be found via B-Matrix. In all, the scheduling algorithm provides an initial, usable schedule in a reasonable amount of time.

Chapter 5. Conclusions and Recommendations

5.1 Specific Contributions

This thesis builds an engine handling SCP associated with Excel Solver. This model combined the concept of SCP, reduced costs, and shadow price to produce a quick and optimal schedule. This model also could be used as an optimization tool finding a solution in SCP with a little model modification.

This research provides LRS scheduler with a scheduling tool based on Microsoft Excel. It is a fast approach for the scheduling problem that incorporates aspects of resource utilization. DSS model performance with the daily recurring jobs is equal to the optimal solution (LP). Pricing algorithm has found the optimal solution in 31 and 62 daily recurring legs and near optimal (one more driver) in 93 and 124 daily recurring legs which are beyond the real situation number. Significant amount of the workload balance is achieved throughout the program. Workload balance tends to transform the SCP into SPP. This model could produce the optimal solution with current workers status. The LRS could not always maintain enough drivers to satisfy all the requirements, and this driver shortage leads to the undesirable results. However, the point is to minimize the penalty value of the unsatisfied duties. This model could handle this kind of problem with “B-Matrix”.

Various parameters’ impact on the number of required drivers was investigated. This parameters consideration will be critical at using this model as an analysis tool. The scheduler may figure out the expected number of drivers with future amount of customers

or legs. This model will provide more advanced insights in future work environment with policy maker such like LRS commander. In brief, DSS model will answer the following kinds of questions: 1) “How many drivers do we need with X amount of customers?” 2) “Which parameter set up is better than current setup? Better means less drivers, less AvgWL, and fully accomplishment of the total legs simultaneously.”

5.2 Recommendations for Future Work

First, this model does not produce full schedule which include the drivers roster, distribute the duties to the real workers and examine a long term workload. This procedure will provide more practical outcomes with the LRS scheduler.

Second, the future research could handle the vehicle routing problem. Throughout this research, vehicle routing within each Zone is fixed by the LRS. The researcher can examine the routes and find more efficient way to execute the mission than current way.

Appendix A. Daily Recurring Responsibilities

Military Duties		Hours
M1	REDBALL / IN-OUT Check - 0700	8
M2	Zone 3 – 0700, 0900, 1300	8
M3	Operator Training (Trainer) - 0700	8
M4	Operator Training (Trainer) - 0700	8
M5	Operator Training - (Trainee) - 0700	8
M6	Operator Training - (Trainee) - 0700	8
M7	Veh Servicing - 0700 (x4), Zone 3 - 1100	6
M8	Veh Servicing - 0700 (x3), Zone 1&2 - 1200, Zone 3 (Extra) - 1200	7
M9	RAFM MICAP - 0800, 1430	9
M10	Zone 7 – 0730, 1300	8
M11	Zone 1&2 - 0800, Zone 3 (Extra)-0800, Zone 1 &2-1000, Zone 3 (Extra)-1000, Zone 1&2-1400, Zone 3 (Extra) -1400	8
M12	Zone 3 – 1500	3
M13	REDBALL / IN-OUT Check - 1600	8
M14	Zone 1&2 - 1600, Zone 3 (Extra)-1600, Zone 1 &2-1800, Zone 3 (Extra)-1800, Zone 1&2 - 2000, Zone 3 (Extra) -2000, Zone 1&2-2200, Zone 3 (Extra) - 2200	8
M15	Zone 3 - 1700, 1900, 2100	6
M16	RAFM MICAP - 2200	3
M17	MID SHIFT - 1900-0700	12

Figure A-1 Current Daily Recurring Responsibilities for Military Personnel

Civilian Duties		Hours
C1	Shuttle - 0600, 1100	8
C2	492 – 0630	8.5
C3	493 – 0630	8.5
C4	494 – 0630	8.5
C5	Veh Servicing - 0700 (x3)	3
C6	Veh Servicing - 0700 (x3)	3
C7	NON-MILSTRIP - 0800, 1300	8
C8	Zone 4&5 - 0800, 1300	8
C9	Zone 6 - 0800, 1300	8
C10	492 – 1500	8
C11	493 – 1500	8
C12	494 – 1500	8
C13	Shuttle – 1600	3
C14	Command Car Svc – 2200	2
C15	MID SHIFT - 1900-0700	12

Figure A-2 Current Daily Recurring Responsibilities for Civilian Personnel

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Vita

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14. ABSTRACT <p>In the US Air Force, a Logistic Readiness Squadron (LRS) provides material management, distribution, and oversight of contingency operations. Dispatchers in the LRS must quickly prepare schedules that meet the needs of their customers while dealing with real-world constraints such as time windows, delivery priorities, and intermittent recurring missions. Currently, LRS vehicle operation elements are faced with a shortage of manpower and lack an efficient scheduling algorithm and tool. The purpose of this research is to enhance the dispatchers' capability to handle flexible situations and produce "good" schedules within current manpower restrictions. In this research, a new scheduling model and algorithm are provided as an approach to crew scheduling for a base-level delivery system with a single depot. A Microsoft Excel® application, the Daily Squadron Scheduler (DSS), was built to implement the algorithm. DSS combines generated duties with the concept of a set covering problem. It utilizes a Linear Programming pricing algorithm and Excel Solver as the primary engine to solve the problem. Reduced costs and shadow prices from subproblems are used to generate a set of feasible duties from which an optimal solution to the LP relaxation can be found. From these candidate duties the best IP solution is then found. The culmination of this effort was the development of both a scheduling tool and an analysis tool to guide the LRS dispatcher toward efficient current and future schedules.</p>					
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